SIMULATION OF HYDROFOIL PERFORMANCE IN CALM WATER

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THESIS

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by

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ABSTRACT

A digital computer simulation program using Digital Simulation Language is produced to study the performance of a hydrofoil in calm water. Various automatic control systems are studied with the model constrained to the pitch-heave-surge mode of operation.

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TABLE OF SYMBOLS

A_F	feet^2	Area of foil
A_S	feet^2	Area of strut
CG	--	Center of gravity
C_{DF}	dimensionless	Drag coefficient of a foil
C_{DS}	dimensionless	Drag coefficient of a strut
C_L	dimensionless	Lift coefficient
C_S	dimensionless	Side force coefficient
F_{DiF}	pounds	Drag force on a foil (water axes)
F_{DiS}	pounds	Drag force on a strut (water axes)
F_{LiF}	pounds	Lift force on a foil (water axes)
F_{SiS}	pounds	Side force on a strut (water axes)
F_X	pounds	Force in direction of body X-axis
F_{XiF}	pounds	Force on a foil in body X-direction
F_{XiS}	pounds	Force on a strut in body X-direction
F_Y	pounds	Force in body Y-direction
F_{YiF}	pounds	Force on a foil in body Y-direction
F_{YiS}	pounds	Force on a strut in body Y-direction
F_Z	pounds	Force in direction of body Z-direction
F_{ZiF}	pounds	Force on a foil in body Z-direction
F_{ZiS}	pounds	Force on a strut in body Z-direction
g_X	feet/second^2	Component of gravity in body X-direction

g_Y	Feet/second^2	Component of gravity in body Y-direction
g_Z	feet/second^2	Component of gravity in body Z-direction
h_S	feet	Height of height sensor above instantaneous water surface
I_{XX}	Slug-foot^2	Mement of inertia about body X-axis
I_{YY}	slug-foot^2	Moment of inertia about body Y-axis
I_{ZZ}	Slug-foot^2	Moment of inertia about body Z-axis
L	foot-pounds	Moment acting to produce roll about body X-axis
L_{XhS}	feet	Distance from CG along X-axis to height sensor
L_{XiF}	feet	Distance from CG along X-axis to a point of foil force
L_{YiF}	feet	Distance from CG along body Y-axis to a point of application of foil force
L_{ZiF}	feet	Distance from CG along body Z-axis to a point of application of foil force
L_{ZiS}	feet	Distance from CG along body Z-axis to a point of application of strut force
M	foot-pounds	Moment acting to produce pitch about body Y-axis
m	slugs	Mass of the craft
N	foot-pounds	Moment acting to produce yaw about body Z-axis
P	radians/second	Roll rate about body X-axis
Q	radians/second	Pitch rate about body Y-axis
R	radians/second	Yaw rate about body Z-axis

S_{EiF}	feet	Submergence of a foil in earth axes
S_{EiS}	feet	Submergence in earth axes of the assumed point of application of strut force
SHP	--	Shaft horsepower
T_X	pounds	Magnitude of thrust in direction of body X-axis
U	feet/second	Velocity in direction of body X-axis
U_E	feet/second	Velocity along earth X-axis
U_i	feet/second	Foil velocity in direction of body X-axis
	feet/second	Total relative velocity
V	feet/second	Velocity in direction of body Y-axis
V_E	feet/second	Velocity along earth Y-axis
V_i	feet/second	Foil velocity in direction of body Y-axis
W	feet/second	Velocity in direction of body Z-axis
W_E	feet/second	Velocity along earth Z-axis
W_i	feet/second	Foil velocity in direction of body Z-axis
X_E	feet	Distance along earth X-axis from reference origin
Y_E	feet	Distance along earth Y-axis from reference origin
α_i	radians	Angle of attack of a particular foil, designated by subscript
β_i	radians	Angle of side slip of particular strut, designated by the subscript
η	dimensionless	Propulsion efficiency

ρ	slugs/foot^3	Water density
ϕ	radians	Roll angle
ψ	radians	Yaw angle
θ	radians	Pitch angle

Subscripts

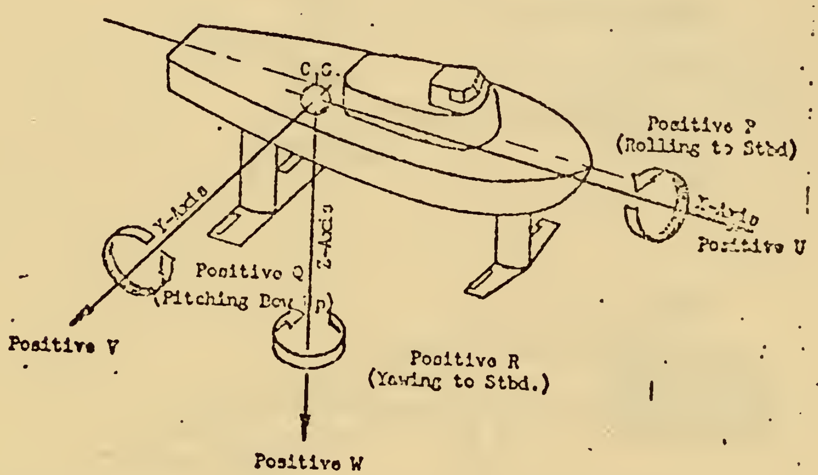
C	Refers to Center foil or strut
P	Refers to Port foil or strut
S	Refers to Starboard foil or strut
M	Refers to Mid foil section
F	Refers to foil
S	Refers to strut
i	When "i" appears in the subscript to a symbol, it indicates that the symbol is to be repeated with i successfully replaced by C, P, S, and M, as indicated

I. INTRODUCTION

A. COORDINATE SYSTEMS

Three coordinate systems will be used in this study of hydrofoil craft dynamics. They are: the body axes, the water axes and the earth axes. Each is a right hand orthogonal system.

The body axes coordinate system (X, Y, Z) shown in figure 1-1 has its origin at the center of gravity of the craft and is fixed relative to the craft. This system is initially coincident with the origin of the earth axes system, however, it moves with the craft as time progresses. X is



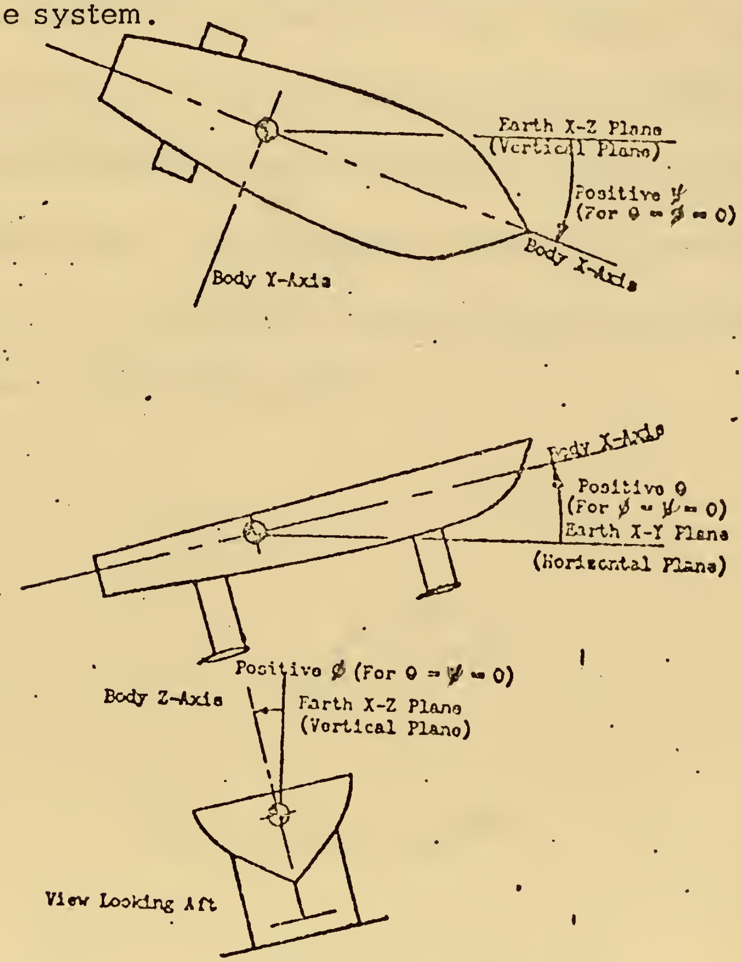
Orientation of the Body Axes with Respect to the Craft and Directions of Positive Velocities
Figure 1-1

positive forward, Y is positive to starboard and Z is positive downward.

The earth axes coordinate system (X_E, Y_E, Z_E) is fixed relative to the earths surface. The origin may be chosen at any convenient location, provided the body system origin is initially at the same point. The X_E

axis lies in the horizontal plane; it is initially coincident with, and positive in the same direction as, the body X axis. The Y_E axis lies in the horizontal plane and is positive to starboard when the observer is facing the positive X_E direction. The Z_E axis is normal to the horizontal and is positive downward. Water surface motion and crafts' motion relative to calm water are described in this coordinate system.

The water axes coordinate system is aligned with the relative velocity vector and resolves into 'lift', 'drag', and 'side force' directions. All hydrodynamic model test data is taken and presented as plots in terms of this coordinate system.



Definition of Positive Directions for Euler Angles

Figure 1-2

[illegible]

Detailed derivations of the transformation matracies between coordinate systems are outlined in Ref. 1 , however, only the results will be considered here. In general, the body axes are displaced from the earth axes by the Euler angles, ϕ , θ , and ψ . Figure 1-2 defines the positive directions for the Euler angles and established the means for transformations between earth and body axes.

The hydrodynamic force and moment data are obtained in a water axis system which is always oriented with respect to the relative water velocity. These data must be transformed into body axes so that their effects can be included in the equations of craft motions. In general, the water axis orientation is always changing with respect to the body axes. This necessitates a transformation to resolve lift, drag, and side force quantities into body axes. The orthogonal water axis coordinate system is defined in figure 1-3. The angles of rotation between water and body axes are α and β and will be defined later.

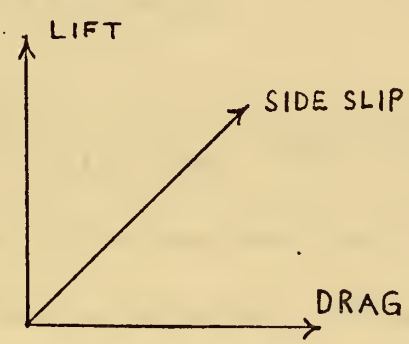


Figure 1-3 Definition of Water Axes

B. EQUATIONS OF MOTION

The development of the six equations of motion for a hydrofoil follow the same classical lines as those for a displacement type hull. This development is clearly outlined in Ref 1 and 4 and therefore will not be done here. The six equations for the hydrofoil are:

Translation

$$\dot{U} = \frac{1}{m} F_x - QW + RV \tag{1-1}$$

$$\dot{V} = \frac{1}{m} F_y + PW - RU \tag{1-2}$$

$$\dot{W} = \frac{1}{m} F_z + QU - PV \tag{1-3}$$

Rotation

$$\dot{P} = \frac{1}{I_{xx}} \left[L - QR(I_{zz} - I_{yy}) + (\dot{R} + QP) I_{xz} \right] \tag{1-4}$$

$$\dot{Q} = \frac{1}{I_{yy}} \left[M - RP(I_{xx} - I_{zz}) - (P^2 - R^2) I_{xz} \right] \tag{1-5}$$

$$\dot{R} = \frac{1}{I_{zz}} \left[N - PQ(I_{yy} - I_{xx}) - (QR - \dot{P}) I_{xz} \right] \tag{1-6}$$

Comparison of actual and simulated data show that the translation terms RV, PV, and PW may be neglected. Similarly, the product of inertia quantity, I_{XZ}, is less than 10% of I_{XX} and 4% less than I_{ZZ}. Consequently, when considered in conjunction with the magnitudes of

(R+PQ), (P^2-R^2) and (QR − P), the terms containing I_{XZ} may be neglected for this craft.

Given the equations 1-1 through 1-6 for linear and rotational accelerations in body axes, the velocity terms in body axes are obtained by merely integrating each equation one time. These outputs must then be transformed to earth axes to be of useful form. The transformation of the linear equations become:

$$U_E = U\cos\theta\cos\Psi + V(\cos\Psi\sin\theta\sin\phi - \sin\Psi\sin\phi) + W(\cos\Psi\cos\theta\cos\phi + \sin\Psi\sin\phi) \qquad (1-7)$$

$$V_E = U\sin\Psi\cos\theta + V(\cos\Psi\cos\phi + \sin\Psi\sin\theta\sin\phi) + W(\sin\Psi\sin\theta\cos\phi - \cos\Psi\sin\phi) \qquad (1-8)$$

$$W_E = -U\sin\theta + V\cos\theta\sin\phi + W\cos\theta\cos\phi \qquad (1-9)$$

Only the crafts velocity in the downward direction is required to compute the crafts height above the water surface. Therefore, the vertical position in earth axes is given by:

$$Z_E = \int W_E\, dt \qquad (1-10)$$

The crafts position in earth axes coordinates is found from:

$$X_E = \int U_E\, dt \qquad Y_E = \int V_E\, dt \qquad (1-11)$$

The Euler angles, ϕ, θ, and Ψ, are also of interest and can be found by integration of the Euler rates $\dot{\phi}$, $\dot{\theta}$, and $\dot{\Psi}$. The rates in turn must be derived from the body angular rates. The Euler rates are not

easily obtained because they occur about axes which are not orthogonal. This fact can be appreciated by referring to figure 1-2 and recalling how the angles were defined. Ψ is a rotation about the Z_o axis, Θ is a rotation about the Y_1 axis, and ϕ is a rotation about the X axis. The results in the following set of equations:

$$\dot{\phi} = P + \dot{\Psi} \sin \Theta \tag{1-12}$$

$$\dot{\Theta} = Q \cos \phi - R \sin \phi \tag{1-13}$$

$$\dot{\Psi} = (Q \sin \phi + R \cos \phi) \cos \Theta + (\dot{\phi} - P) \sin \Theta \tag{1-14}$$

Studies of this craft show that even under the most drastic abnormal situations, pitch angles are not expected to reach 10° and under normal operating conditions, roll angles will not exceed 3°. Therefore, the following assumptions are justified:

$$\begin{aligned} \sin \Theta &= \Theta \\ \cos \Theta &= 1 \end{aligned} \tag{1-15}$$

The Euler angles are obtained by integration of equations 1-12, 13, 14.

C. CALCULATION OF VELOCITY COMPONENTS

The various foil velocity components must be determined at this point in order to calculate the angles of attack and side slip. The total velocity components of each foil in body axes can be expressed in terms of the craft linear and angular velocities by considering the craft geometry as represented in figure 1-4 and Table 1.

The resultant foil relative velocity equations become:

Center foil

$$U_c = U + L_{ZCF} Q \tag{1-16}$$

$$V_c = V - L_{ZCF} P + L_{XCF} R \tag{1-17}$$

$$W_c = W - L_{XCF} Q \tag{1-18}$$

Port foil

$$U_P = U + L_{ZPF} Q - L_{YPF} R \tag{1-19}$$

$$V_P = V - L_{ZPF} P + L_{XPF} R \tag{1-20}$$

$$W_P = W - L_{YPF} P - L_{XPF} Q \tag{1-21}$$

Starboard foil

$$U_S = U + L_{ZSF} Q - L_{YSF} R \tag{1-22}$$

$$V_S = V - L_{ZSF} P + L_{XSF} R \tag{1-23}$$

$$W_S = W + L_{YSF} P - L_{XSF} Q \tag{1-24}$$

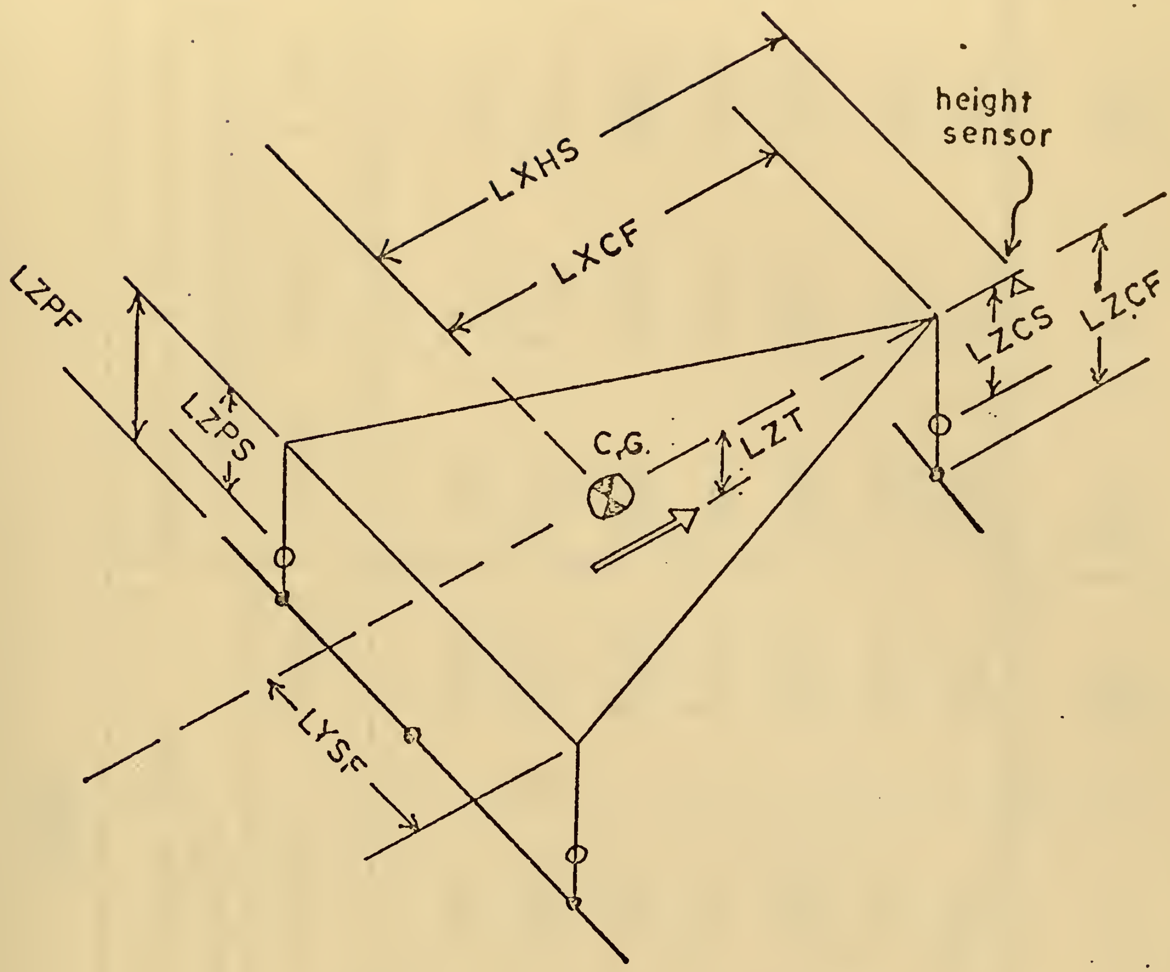


Figure 1-4 Definition of Symbology

Key:

● = point of application of foil forces

o = point of application of strut forces

Note:

$L_{XCF} = L_{XCS}$

$L_{XPF} = L_{XPS} = L_{XSF} = L_{XSS} = L_{XMF}$

$L_{YSF} = L_{YSS} = -L_{YPF} = -L_{YPS}$

$L_{ZPF} = L_{ZSF} = L_{ZMF}$

L_{ZPS} and L_{ZSS} are variables and in general will not be equal.

TABLE 1

Point of Application of Force	Symbol for Force Along or Parallel to			Coordinate From CG to Point of Application Relative to		
	X-Axis	Y-Axis	Z-Axis	X-Axis	Y-Axis	Z-Axis
Center Foil	F_{XCF}	F_{YCF}	F_{ZCF}	L_{XCF}	L_{YCF}	L_{ZCF}
Center Strut	F_{XCS}	F_{YCS}	F_{ZCS}	L_{XCS}	L_{YCS}	L_{ZCS}
Port Foil	F_{XPF}	F_{YPF}	F_{ZPF}	L_{XPF}	L_{YPF}	L_{ZPF}
Port Strut	F_{XPS}	F_{YPS}	F_{ZPS}	L_{XPS}	L_{YPS}	L_{ZPS}
Starboard Foil	F_{XSF}	F_{YSF}	F_{ZSF}	L_{XSF}	L_{YSF}	L_{ZSF}
Starboard Strut	F_{XSS}	F_{YSS}	F_{ZSS}	L_{XSS}	L_{YSS}	L_{ZSS}
Mid Foil Segment	F_{XMF}	F_{YMF}	F_{ZMF}	L_{XMF}	L_{YMF}	L_{ZMF}
Effective Point of Application of Prop. Thrust	T_X	0	T_Z	L_{XT}	0	L_{ZT}

Mid foil

$$U_M = U + L_{zMF}\, Q \qquad (1\text{-}25)$$

$$V_M = V - L_{zMF}\, P + L_{xMF}\, R \qquad (1\text{-}26)$$

$$W_M = W - L_{xMF}\, Q \qquad (1\text{-}27)$$

These foil velocities are in body axis terms and can be used directly to calculate the angles of attack and angles of side slip.

The angle of attack of the foil is shown in figure 1-5a and defined as the angle whose tangent is the total relative velocity between the water and the foil in the body Z direction, divided by the total relative velocity between the water and foil in the body X direction.

$$\alpha = \text{ARCTAN}\, \frac{W_r}{U_r} \qquad (1\text{-}28)$$

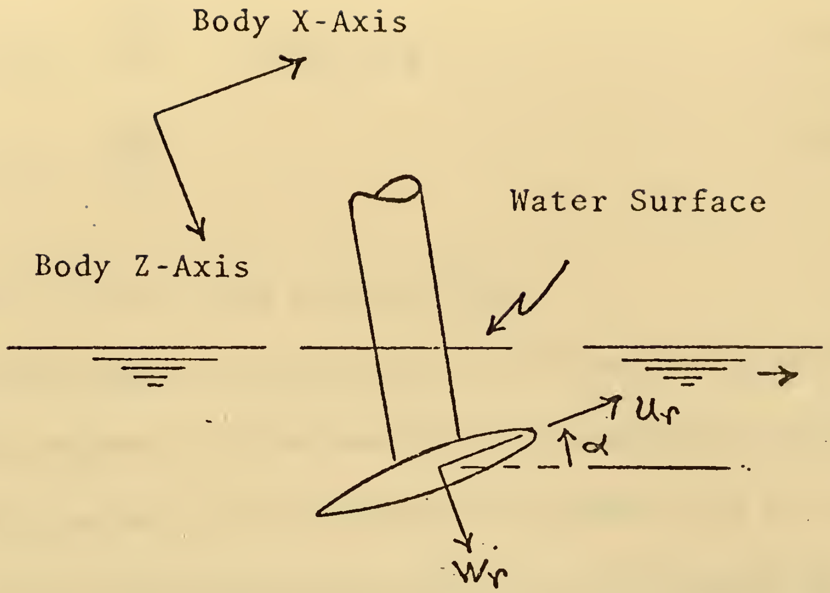
If the foil is not aligned with the body X axis, then the foil has a fixed angle of attack and the total angle of attack becomes:

$$\alpha_{total} = \alpha_{fixed} + \alpha \qquad (1\text{-}29)$$

The side slip angle is shown in figure 1-5b and can be represented by:

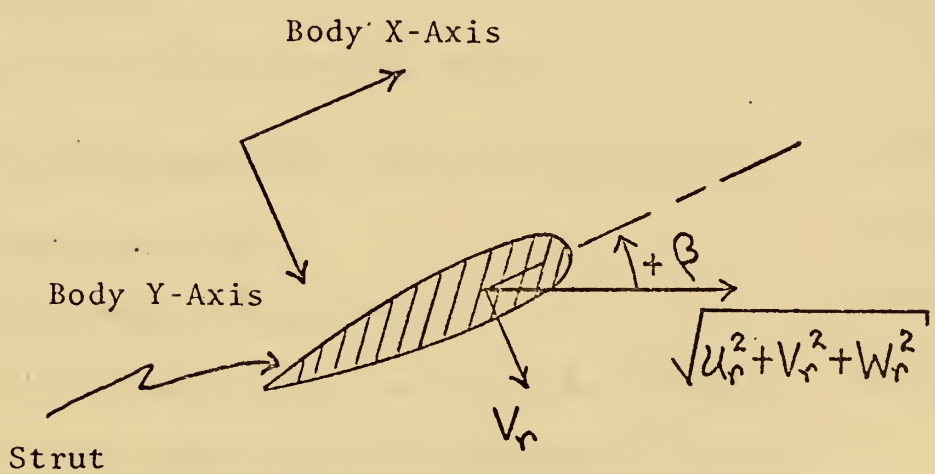
$$\beta_i = \text{ARCSIN}\, \frac{V_{ri}}{\sqrt{U_{ri}^2 + V_{ri}^2 + W_{ri}^2}} \qquad (1\text{-}30)$$

During actual craft operations, the angles of and will be less than 10° permitting use of the small angle approximation. Also, the V and W velocities can be considered very small in relation to the U velocity. Applying these simplifications, the equations for α and β become:



(a)

ANGLE OF ATTACK



(b)

ANGLE OF SIDE SLIP

Figure 1-5

$$\alpha_i = \frac{W_{ri}}{u} + \alpha_{i\text{-fixed}} \qquad (1\text{-}31)$$

$$\beta_i = \frac{V_{ri}}{u} \qquad (1\text{-}32)$$

D. EXPANSION OF FORCE AND MOMENT TERMS

With the aid of figure 1-4 and Table 1, the forces and moments for the craft are easily written. It is important to note, that when a numerical value is substituted for one of the alphabetical dimensions, the sign must be positive or negative depending on the relative position from the CG.

One of the assumptions made upon commencing simulation was that the struts contributed zero lift and that the foils contributed zero side force. Therefore, all body Y motion originates at the struts and all body Z motion originates at the foils.

The force and moment equations become:

$$F_X = F_{XCF} + F_{XPF} + F_{XSF} + F_{XMF} + F_{XCS} + F_{XPS} + F_{XSS} + mg_X + T_X \qquad (1\text{-}33)$$

$$F_Y = F_{YCS} + F_{YPS} + F_{YSS} + mg_Y \qquad (1\text{-}34)$$

$$F_Z = F_{ZCF} + F_{ZPF} + F_{ZSF} + F_{ZMF} + mg_Z \qquad (1\text{-}35)$$

$$L = (F_Z L_Y)_{PF} + (F_Z L_Y)_{SF} - (F_Y L_Z)_{PS} - (F_Y L_Z)_{SS} - (F_Y L_Z)_{CS} \qquad (1\text{-}36)$$

$$\begin{aligned} M = &-(F_Z L_X)_{CF} - (F_Z L_X)_{PF} - (F_Z L_X)_{SF} - (F_Z L_X)_{MF} + (F_X L_Z)_{CF} \\ &+ (F_X L_Z)_{PF} + (F_X L_Z)_{SF} + (F_X L_Z)_{MF} + (F_X L_Z)_{CS} \\ &+ (F_X L_Z)_{PS} + (F_X L_Z)_{SS} + T_X L_{ZT} \end{aligned} \qquad (1\text{-}37)$$

$$N = (F_Y L_X)_{CS} + (F_Y L_X)_{PS} + (F_Y L_X)_{SS} \qquad (1\text{-}38)$$

All of these forces have a hydrodynamic origin except for the thrust and gravity terms. The thrust is always associated with the body axis and requires no further expansion. The gravity terms can be simplified using the small angle approximation for the Euler angles. (See summary of equations A-31, 32, 33.)

The general expression for hydrodynamic forces in water axes coordinates is

$$F_i = q\,A\,C_i \qquad i = L, D, S \tag{1-39}$$

where L, D, S represent lift, drag and side force respectively. The lift, drag, and side force coefficients vary as functions of angle of attack, angle of side slip, submergence, velocity, flap and rudder positions.

Ideally, mathematical expressions would have been developed to correctly depict the interrelation of all the variables which affect the force coefficients. However, hydrofoil technology has not advanced to a position which would yield such expressions. Some of the major problems encountered in deriving a mathematical expression are:

1) The occurrence of cavitation and ventilation which are completely unpredictable.

2) Even more unpredictable is the cessation of cavitation and ventilation.

3) The nonlinearity of the hydrodynamic coefficients.

4) Lack of sufficient test data to completely describe all of the above.

II. HYDROFOIL SIMULATION

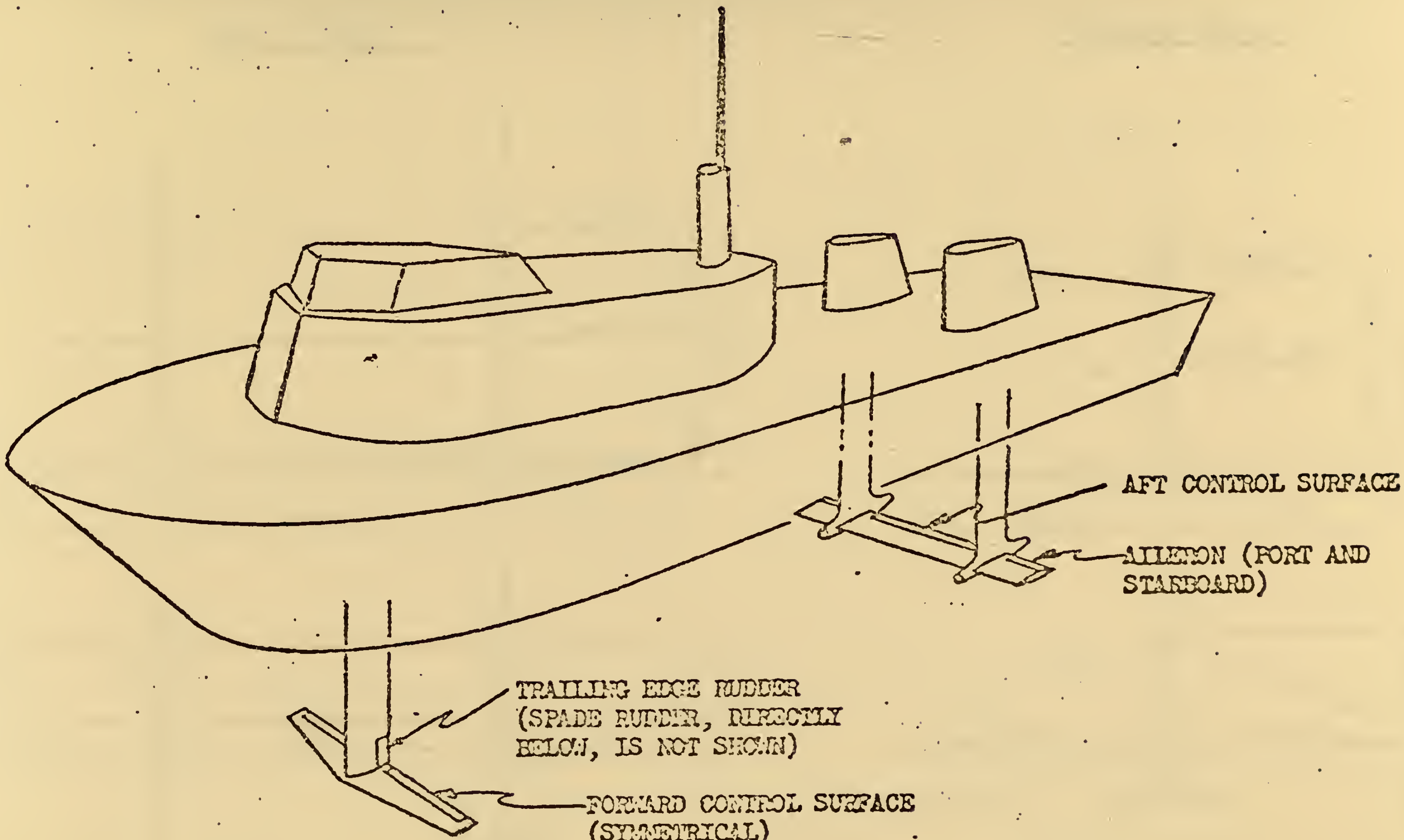
Given the equations of motion, the next step was to formulate a program which would simulate the model. The computer language chosen was Digital Simulation Language or DSL. DSL was chosen over FORTRAN because of its adaptability to control problems and the ease with which the user can insert engineering relationships with a minimum amount of programming.

This computer simulation is designed for the HIGH POINT PC(H)-1 which has a canard foil-strut configuration. Drawings of the craft and the foils are shown in figures 2-1 and 2-2. The after foil is one unit, but in the equations, it is considered to be divided into three separate segments, i.e. mid panel and port/starboard outboard panels.

The following assumptions were made prior to beginning simulation:

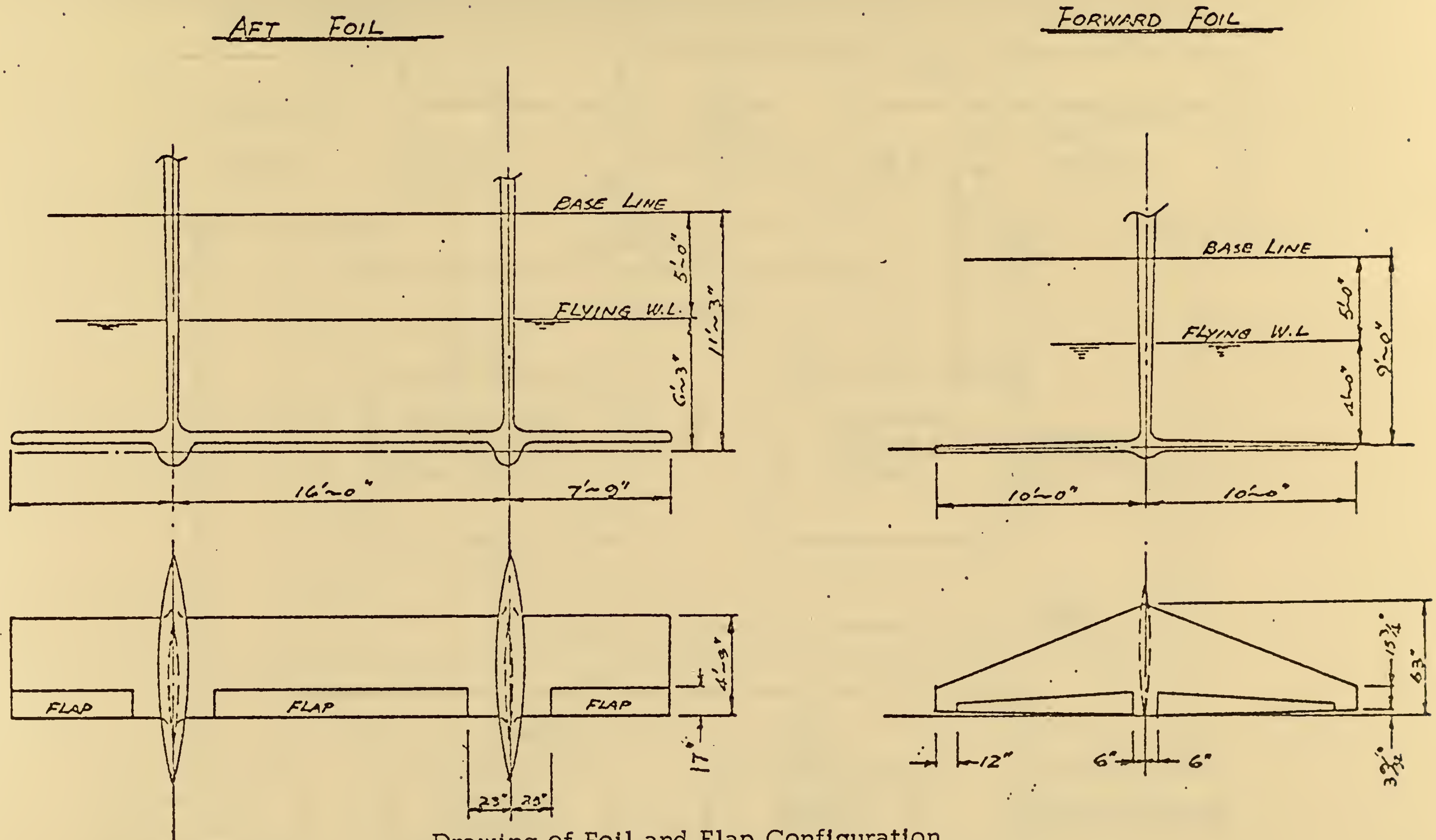
1. Craft equations of motion are valid only for the foilborne mode.
2. Weight of the craft remains constant.
3. Hydrodynamic coefficients are based on fully wetted surfaces, i.e. no cavitation or ventilation.
4. No constraint was placed on crafts heading.
5. Foils are considered flat surfaces vice dihedral/anhedral.
6. The craft has no automatic control system.
7. The craft may be operated in calm water or in a seaway.

Before the main program could be assembled, subroutines had to be written to find the hydrodynamic coefficients of foil lift and drag, and strut drag and side slip. Using the simulation curves in Ref. 3 as a guide, the



Drawing of Foil and Strut Configuration

Figure 2-1



Drawing of Foil and Flap Configuration

Figure 2-2

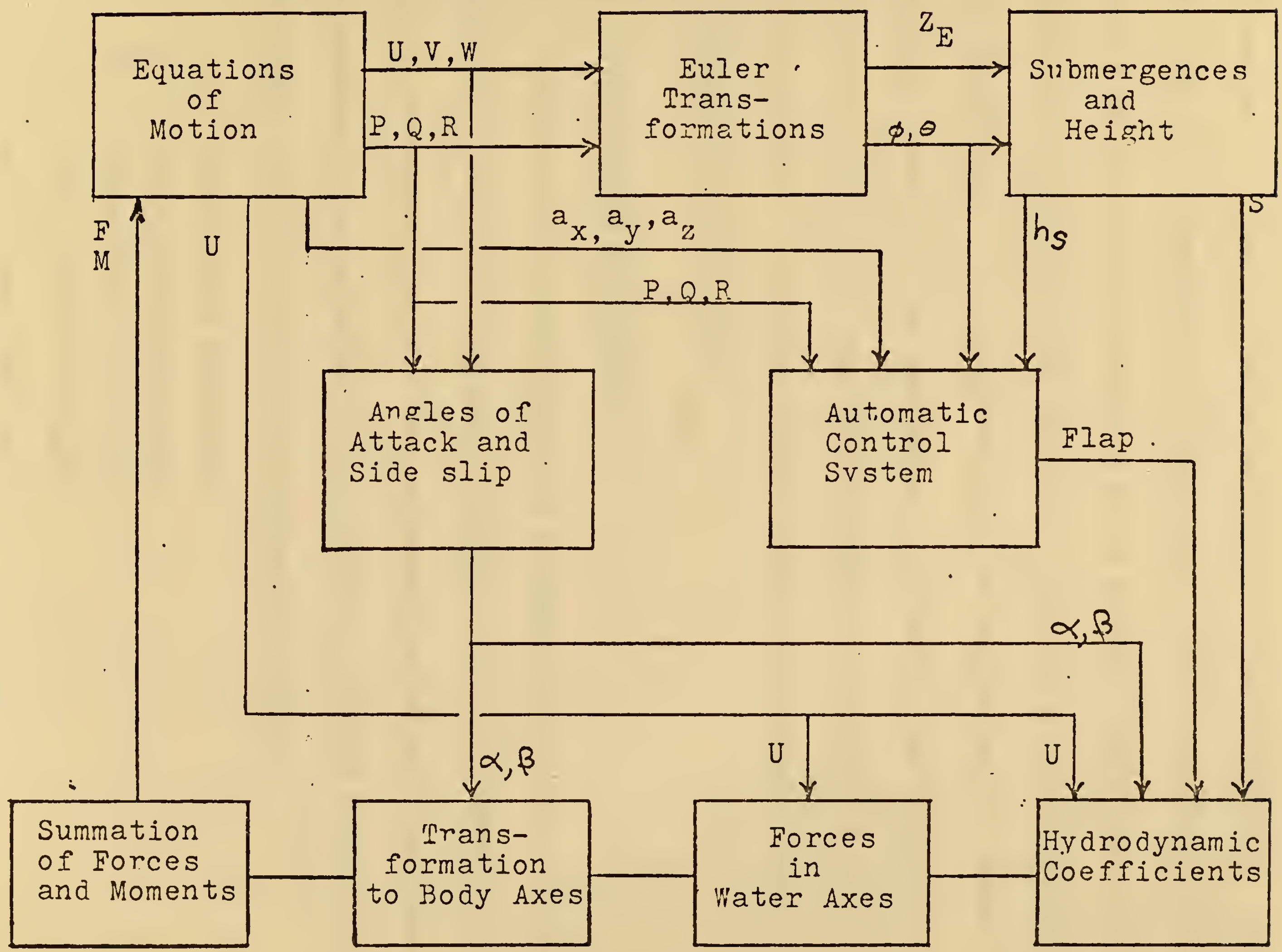


Figure 2-3. Block Diagram of Equation Relationships

curves were stored as data points in the SETUP routine. The subroutines INTERP and INTRP1 are interpolation routines to obtain the proper coefficient from the curves. For INTERP, values of angle of attack and flap angle are used to enter the curves and obtain a value of foil drag. Angle of side slip and submergence are used to enter INTRP1 to obtain strut drag. The curve for the lift coefficient of a foil in the fully wetted region is a straight line so this coefficient is found by merely solving the equation for the straight line. Curves plotted from the subroutines are shown in Appendix B. Listings of the subroutines are shown in the Computer Program section. The main program was then assembled using figure 2-3 as a reference for data flow. A complete listing of the main program is shown in the Computer Program section.

A. SIMULATION OBJECTIVES

The object of the simulation was to commence the runs with the craft foilborne and in a steady state condition. Once this condition was achieved, the step-response of the craft would be studied by applying step functions to excite motion along and about each body axis. That is, perturbations should be introduced to separately excite:

1. Motion along the X-axis
2. Motion about the X-axis
3. Motion along the Y-axis
4. Motion about the Y-axis
5. Motion along the Z-axis
6. Motion about the Z-axis

After the step response was obtained, a sinusoidal sea would be inserted to observe the crafts motion in a seaway.

B. PROBLEMS ENCOUNTERED

There were three major problems encountered during the simulation that are worthy of discussion: (1) the unknown stability of the craft, (2) specification of units used in the derivation of the equations, and (3) numerical quantities for thrust versus speed.

1. Craft Stability

One of the first assumptions made was that the craft would be stable in the foilborne mode with no control system. Starting from this assumption, the first consideration became that of balancing all of the forces and moments. A speed of 36 knots was chosen to insure that cavitation did not exist at any of the wetted surfaces and that the control surfaces were zero. The fixed angle of attack was assumed zero.

It was readily apparent that zero fixed angle of attack was an invalid assumption because the angle of attack was to be the controlling parameter in stabilizing the model. Reference 5 listed the fixed angles of attack as 0 .332 forward and 0.0558 aft. These values were used, but the model became unstable at approximately 4.9 seconds. Only slight variations of angle of attack above and below a critical value caused the model to either raise out of the water or to sink. This pointed out the strong dependence of both lift and drag upon the angle of attack and the problem of balancing the force and moment equations. Referring back to

equations 1-33 through 1-38, one can appreciate the complexity involved in balancing these equations as they are all interrelated. In order to simplify the problem at all, only the forces in the body X and Z directions and the moment about the Y axis were considered. Another simplification was that of considering the entire forward foil as a control surface. The Angle of Attack program was then written to solve for the angle of attack which minimized the force in the body Z direction and the moment about the body Y axis. Once the force and moment were minimized, the program then checked the force in the body X direction and adjusted thrust to minimize it. A listing of this program, which is straight FORTRAN, is shown in the Computer Program section. The angles of attack determined from this program were then inserted into the main program. Significant results were obtained, however, the model remained unstable. This indicated that there was no feedback to dampen the error, so the model was functioning as an open loop system. Considering the output quantities to be linear accelerations and velocities, angular rates and angular positions, while the input quantity is reference height above calm water and $\underline{X}_C$ is the measured quantity which is fed back, the block diagram can be represented as shown in figure 2-3. No graphs are shown of this mode because of the instability of the model.

Stability of the model without a control system was questioned at this point and it was determined that assumption #6, i.e. the craft has no automatic control system, was invalid. Reference 5 confirmed the fact that the model was only stable in three degrees of freedom without a control

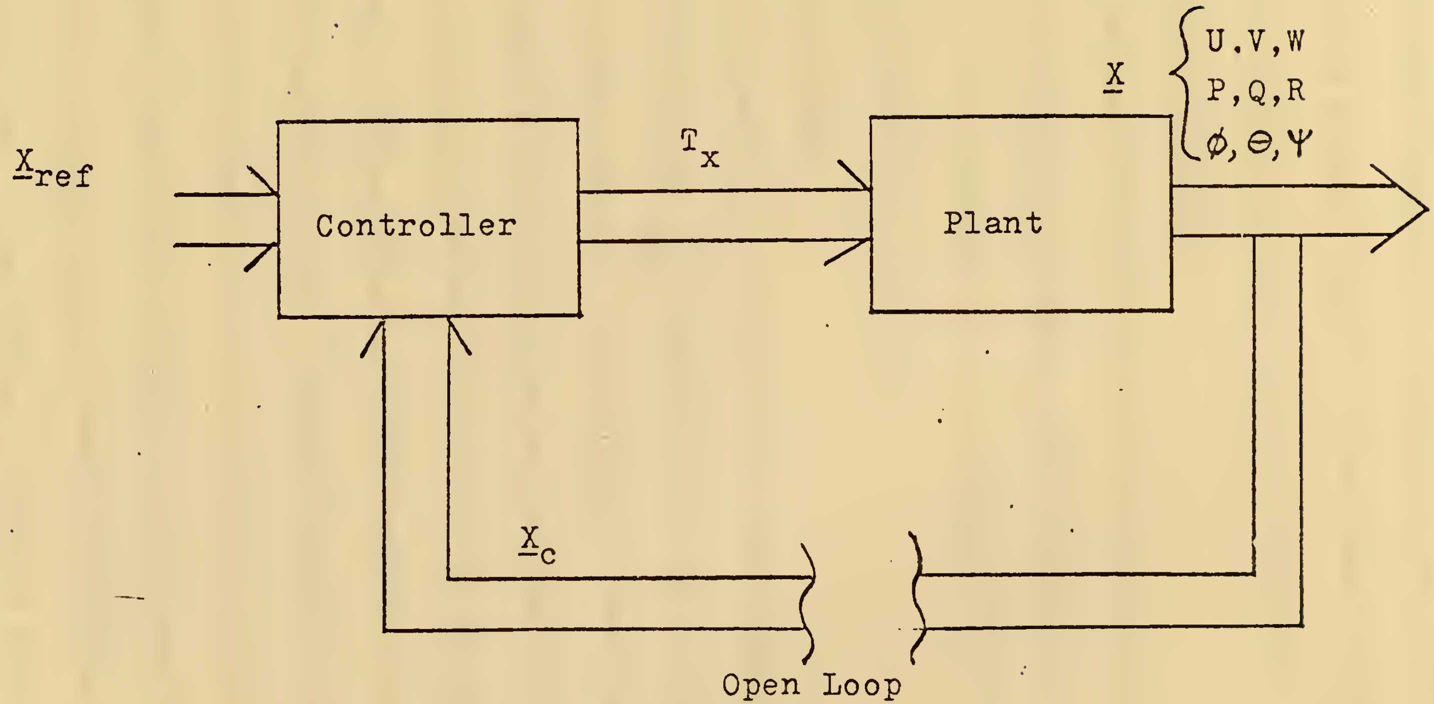


Figure 2-4. Block Diagram Of System With Open Loop

system. Additionally, it was determined that when the model was constrained to the pitch-heave-surge mode of operation it was still only marginally stable without a control system. At this point, a control system was added and it will be discussed in detail in Chapter III.

2. Specification of Units

Considerable confusion resulted from the interpretation of the various references concerning the units used in defining Euler angles and angular rotations. This problem has been alleviated here by the specific definitions in the Table of Symbols.

3. Thrust vs Speed

Since no graphical or numerical data was available to show the thrust vs speed relationship, the computer was utilized to determine a value of thrust for a given speed. Once the Angle of Attack program had found the proper angle of attack to minimize the force and moment, the program then checked the force in the body X direction and adjusted the thrust to minimize this force. This produced an initial condition for thrust which was then inserted in the main program. The main simulation program incorporated a thrust trim routine which is shown on the main listing.

The thrust trim routine compares the magnitude of the force in the X direction with the thrust and then tests the difference with an arbitrarily small fixed error. If the difference is greater than the error, then thrust is set equal to the value necessary to make the force in the X direction equal to zero. At the same time, the acceleration in the X

direction is also set equal to zero. If the difference is less than the error, then the thrust is held constant and the acceleration in the X direction is allowed to vary.

III. AUTOMATIC CONTROL SYSTEM

Once it became apparent that the model would remain unstable without a control system, the only alternative was to add the control system. As was previously stated, the problem will be greatly simplified by constraining the model to the pitch-heave-surge mode of operation. In so doing, the control system can be limited to the forward foil. It was assumed that once the control system for the forward foil was operational, it could be easily extended to the after foil.

A. HEIGHT SENSOR

For this control system, a height sensor was incorporated which sensed the change in height of the CG above calm water. This change was utilized as a positional feedback signal to control the flap angle on the forward foil. This was accomplished in the simulation by defining the reference height of the CG for the particular speed and subtracting the actual height to obtain a difference called DELH. This difference was multipled by a gain factor to produce the variable FLAP defined as:

$$\text{FLAP} = \text{DELH*COEFH} \tag{3-1}$$

Figure 3-1 shows the contents of the automatic control block in the program listing. Figure 3-2 is the block diagram of this system showing submergence height as the measured quantity being fed back to the controller.

[illegible]

The amount of flap is governed by the unbalance of the equations of motion. Since the flap angle is directly proportional to both lift and drag it makes a significant contribution to the balancing of the equations of motion. A parameter study was made and determined that the optimum value for COEFH was 0.85. Figures 3-3, 4, 5 show the response of the model to a positive 5 deg/sec disturbance applied to Q for 0.2 seconds. It must be pointed out that with the configuration used, the flap was capable of moving instantaneously because an inertia term had not yet been added.

With the model stable using position feedback, the next refinement was that of utilizing acceleration, velocity and position signals for feedback. It was realized very quickly that this was an unrealistic approach.

B. RATE FEEDBACK

With the model stable using position feedback, the next refinement was that of utilizing acceleration, velocity, and position signals for feedback. It was realized very quickly that this was an unrealistic approach in that two of the three feedback signals were measured at the CG, therefore, neglecting any pitch component. The equation for flap then becomes:

$$\mathrm{FLAP} = \mathrm{GAIN1\ DELH} - \mathrm{GAIN3}\ \dot{W} - \mathrm{GAIN4}\ W \qquad (3\text{-}2)$$

where GAIN1, GAIN3, and GAIN4 are gain constants. Figure 3-6 shows the contents of the automatic control block for this system and figure 3-7 is the block diagram. The model became unstable for all values except

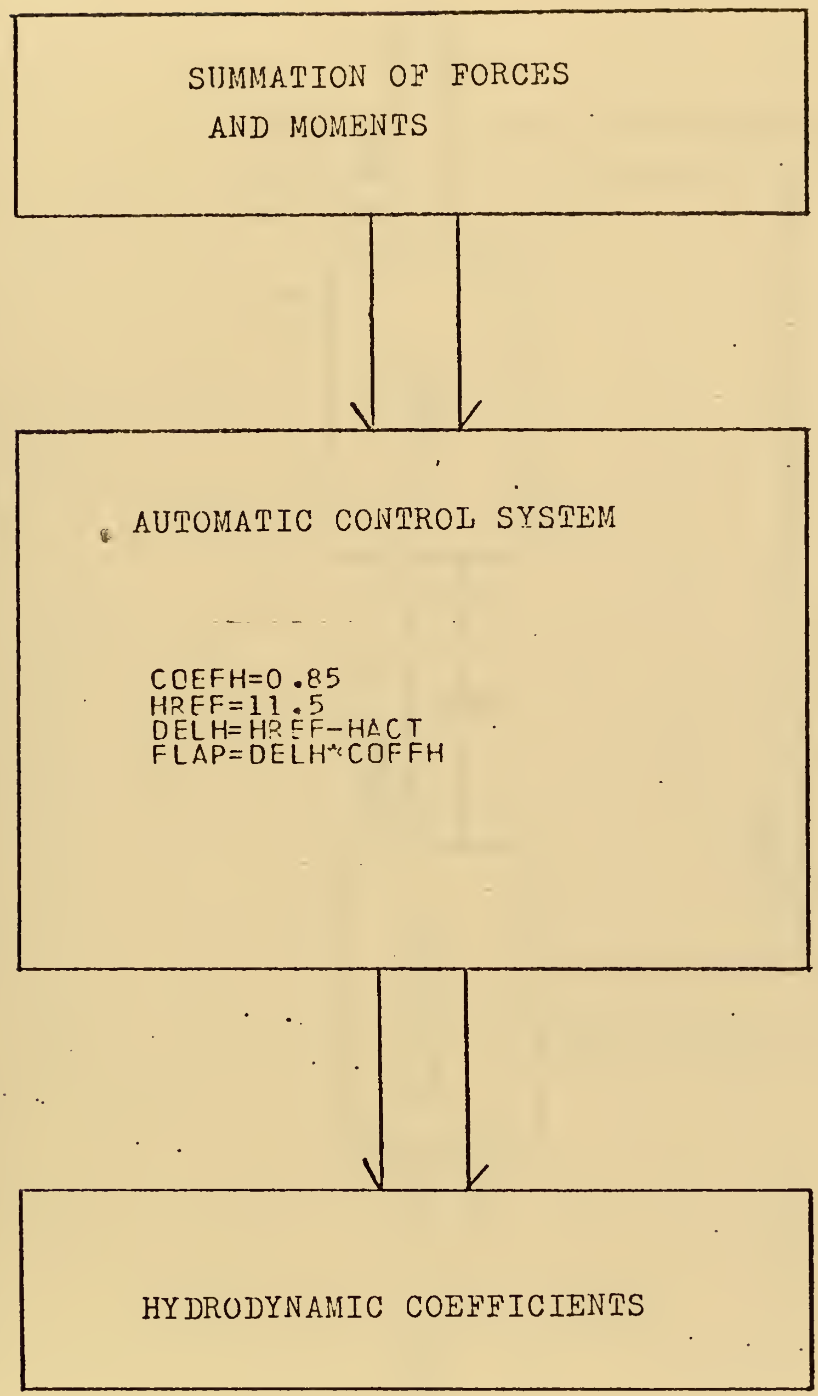


Figure 3-1. Automatic Control Block for Height Sensor

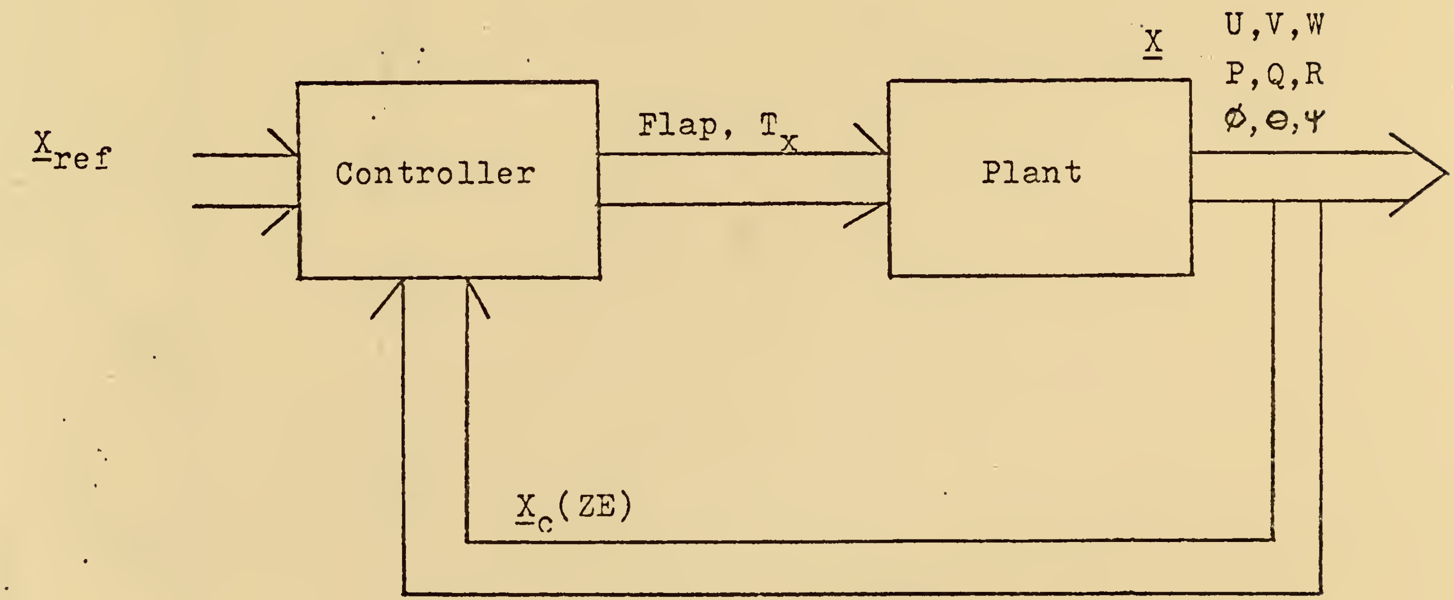
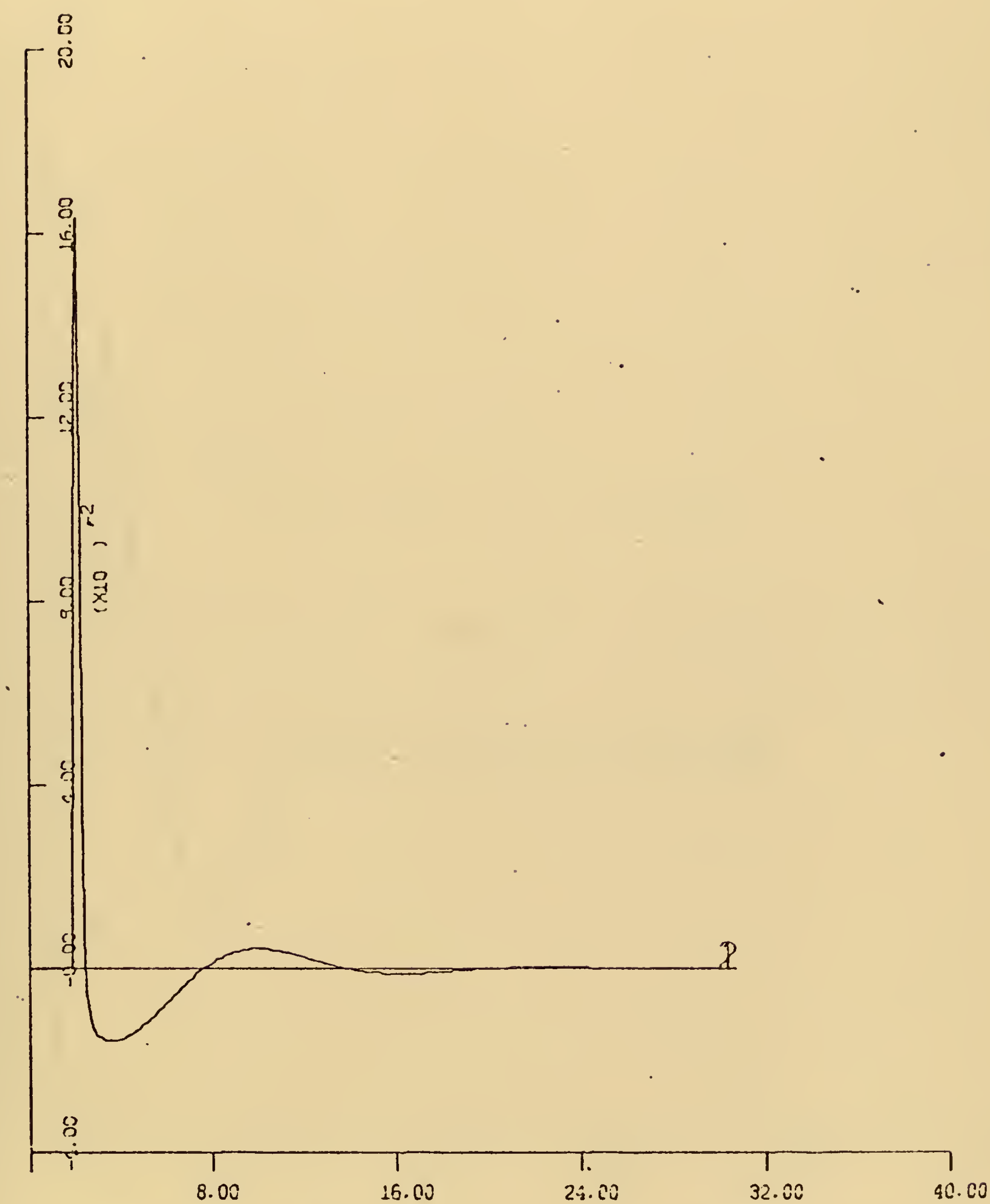


Figure 3-2. Block Diagram Showing Height Feedback

Pitch Rate vs Time
Height Sensor Only

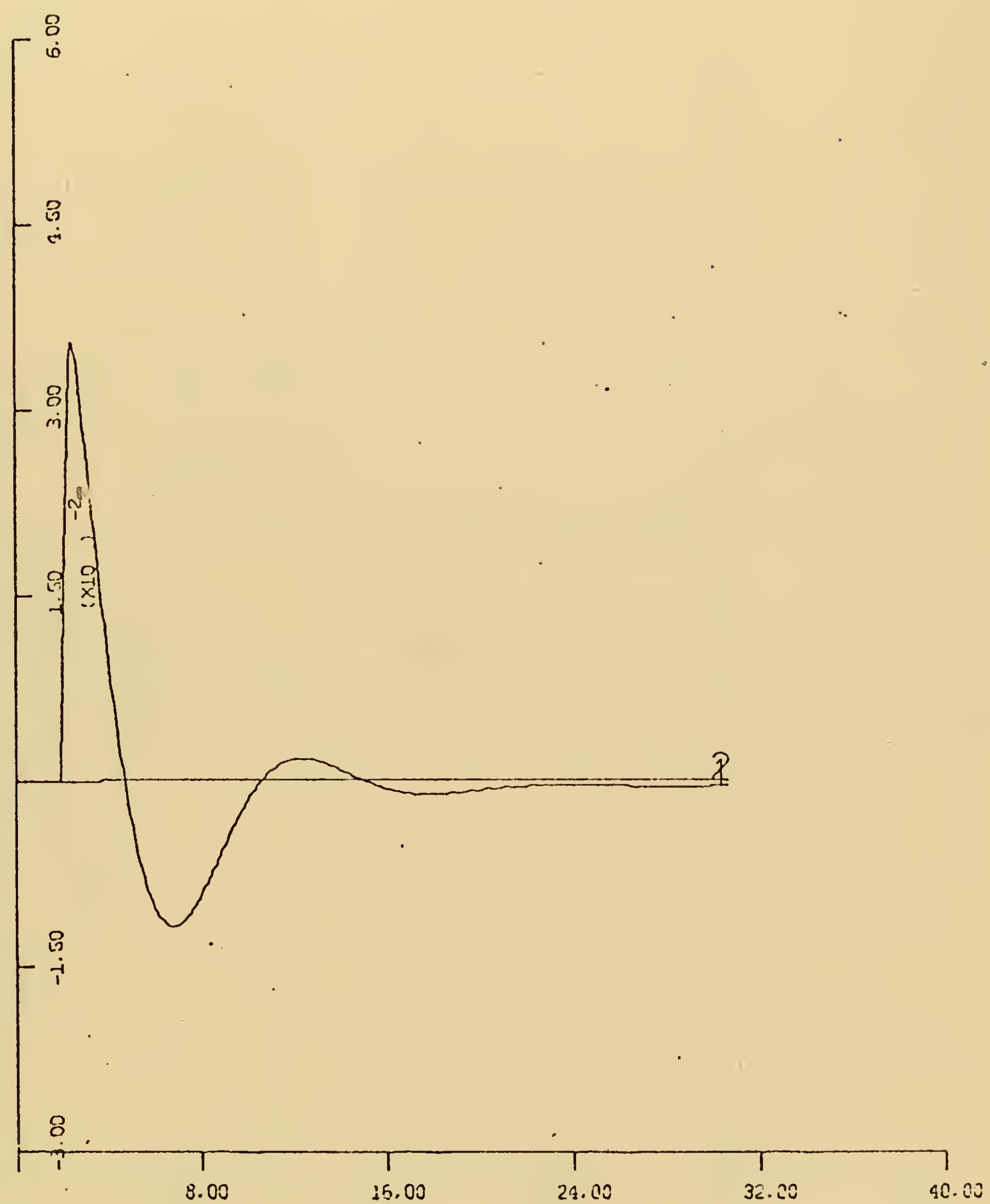


X-Scale = 8 seconds/inch
Y-Scale = 0.04 radians/second

COEFH = 0.85

Figure 3-3

Pitch Angle vs Time
Height Sensor Only

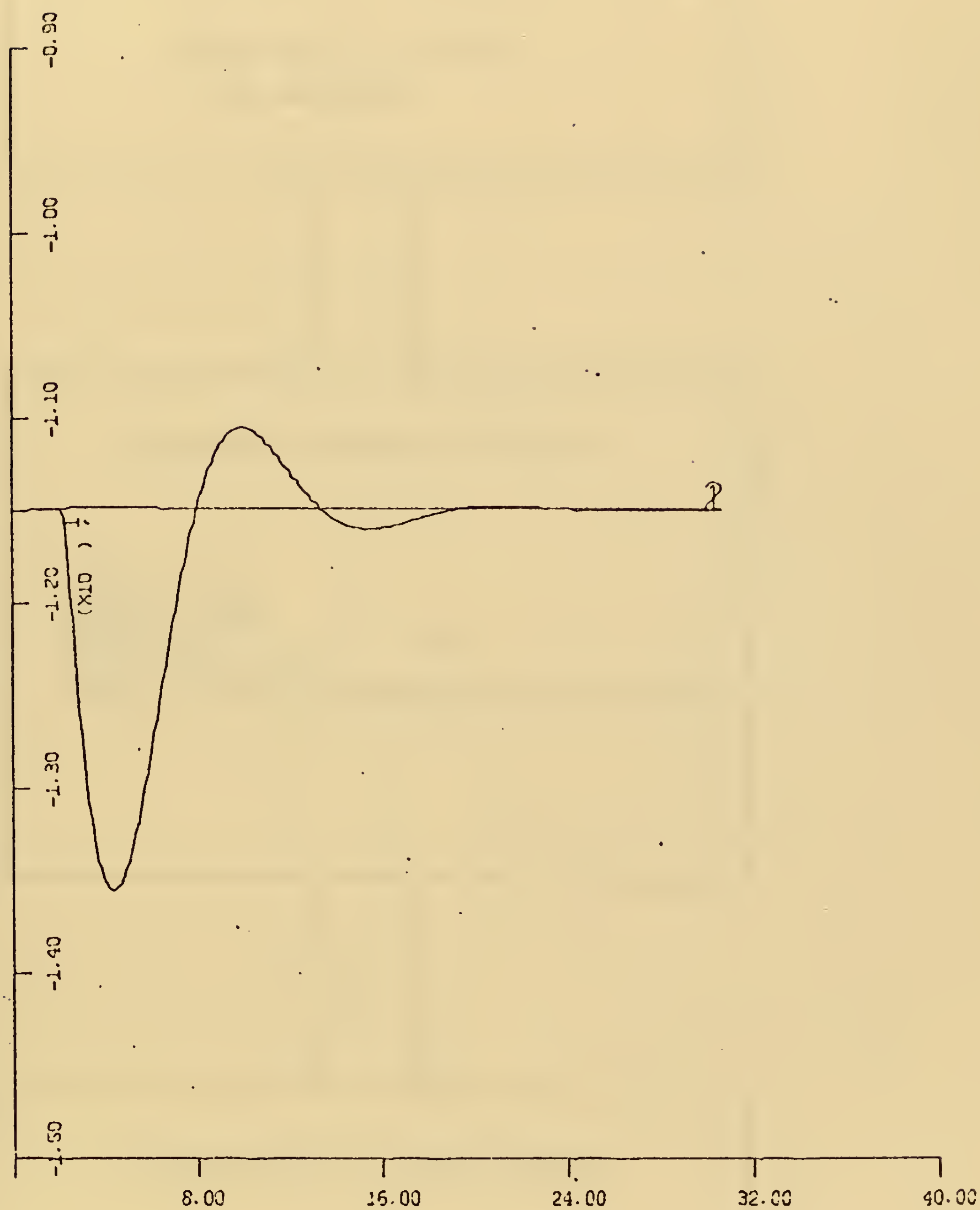


X-Scale = 8 seconds/inch
Y-Scale = 0.02 radians/inch

COEFH = 0.85

Figure 3-4

Submergence vs Time
Height Sensor Only



X-Scale = 8 seconds/inch
Y-Scale = 1 foot/inch

COEFH = 0.85

Figure 3-5

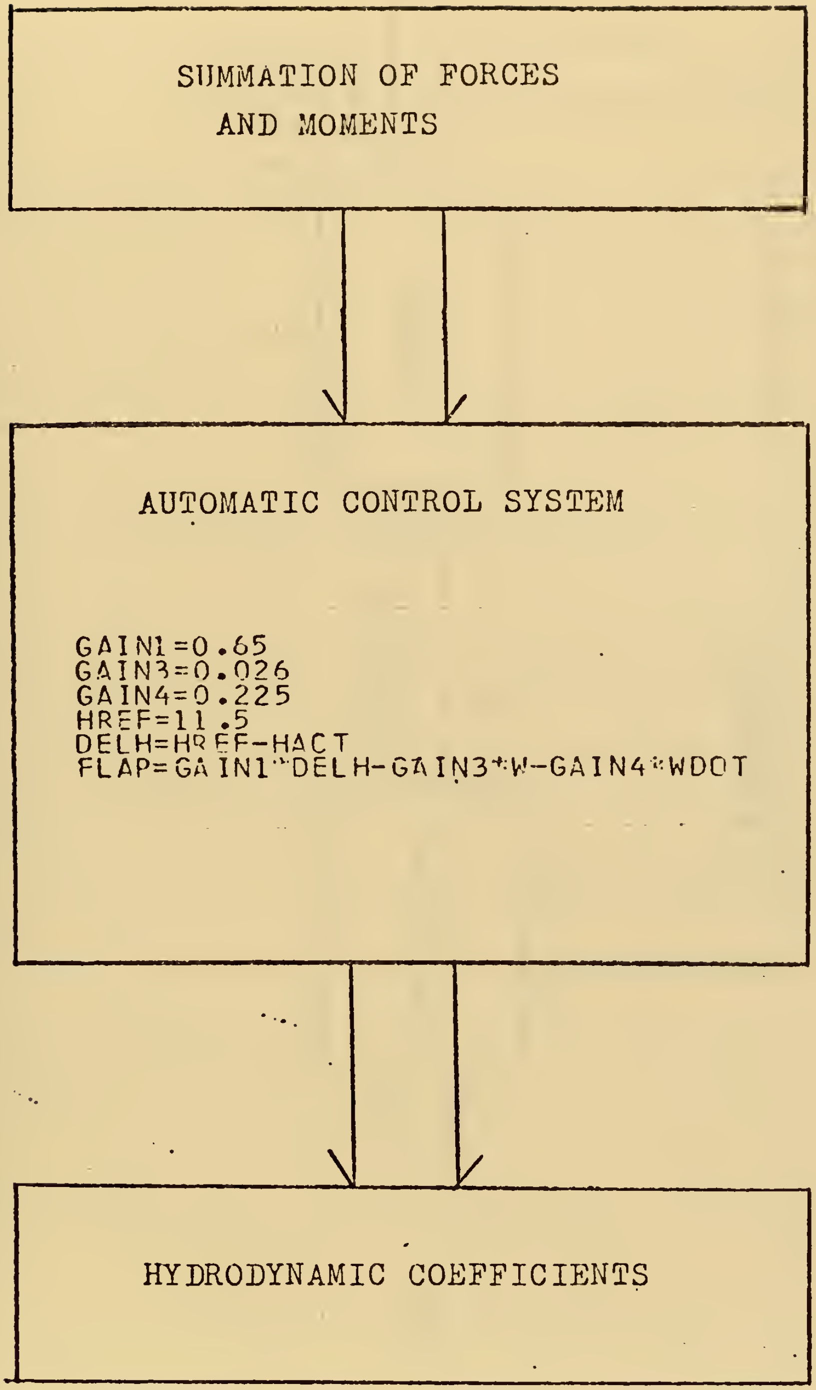


Figure 3-6. Automatic Control System for Rate Feedback

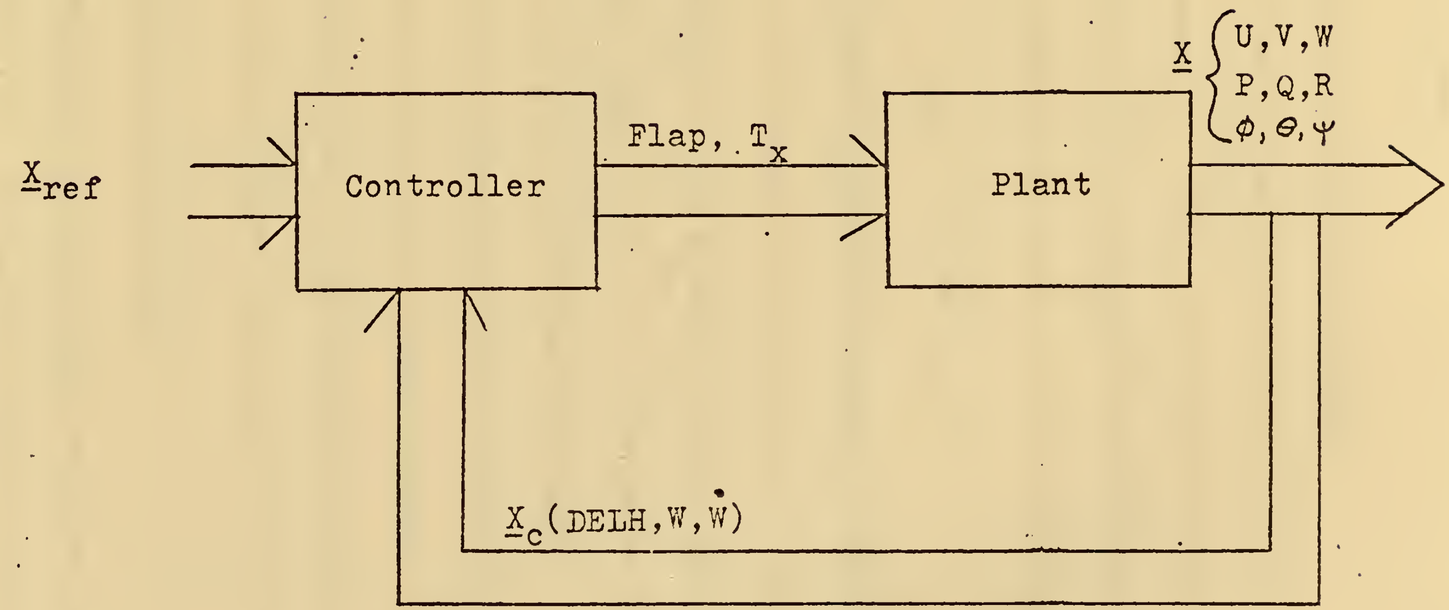


Figure 3- 7 . Block Diagram Showing Rate Feedback

zero, of GAIN3 and GAIN4. No graphs were plotted because of the unstability of the system.

C. RATE FEEDBACK WITH ACCELEROMETER

This system was implemented by using an accelerometer to sense motion at the forward foil. The accelerometer corrects the body vertical acceleration by the pitch rate translated to the forward foil. This produces the true acceleration at the forward foil. The equation is given by:

$$A_{ZC} = (F_Z/m) - L_{XCF}\dot{Q} \tag{3-3}$$

Figure 3-8 shows the contents of the automatic control block for this system and figure 3-9 shows the block diagram. This control system provided stable operation as long as GAIN3 was less than 0.02 and GAIN4 was less than 0.2. Figures 3-10, 11, 12 are graphs of the system response to the same disturbance stated previously.

All three of the systems listed so far were not physically realizable in that the flap was provided instantaneous response to any error signal. This is not the case in a real system because the flap possesses a finite amount of inertia which produces a time lag in the response.

D. RATE FEEDBACK WITH REAL POLE

The instantaneous response problem was taken care of in this system by adding an inertia term. This entails adding a pole to the root locus and placing it on the real axis in the left half plane. The addition of the pole helped to stabilize the system, but also increased the overshoot and and time lag. The time lag associated with the real pole caused the

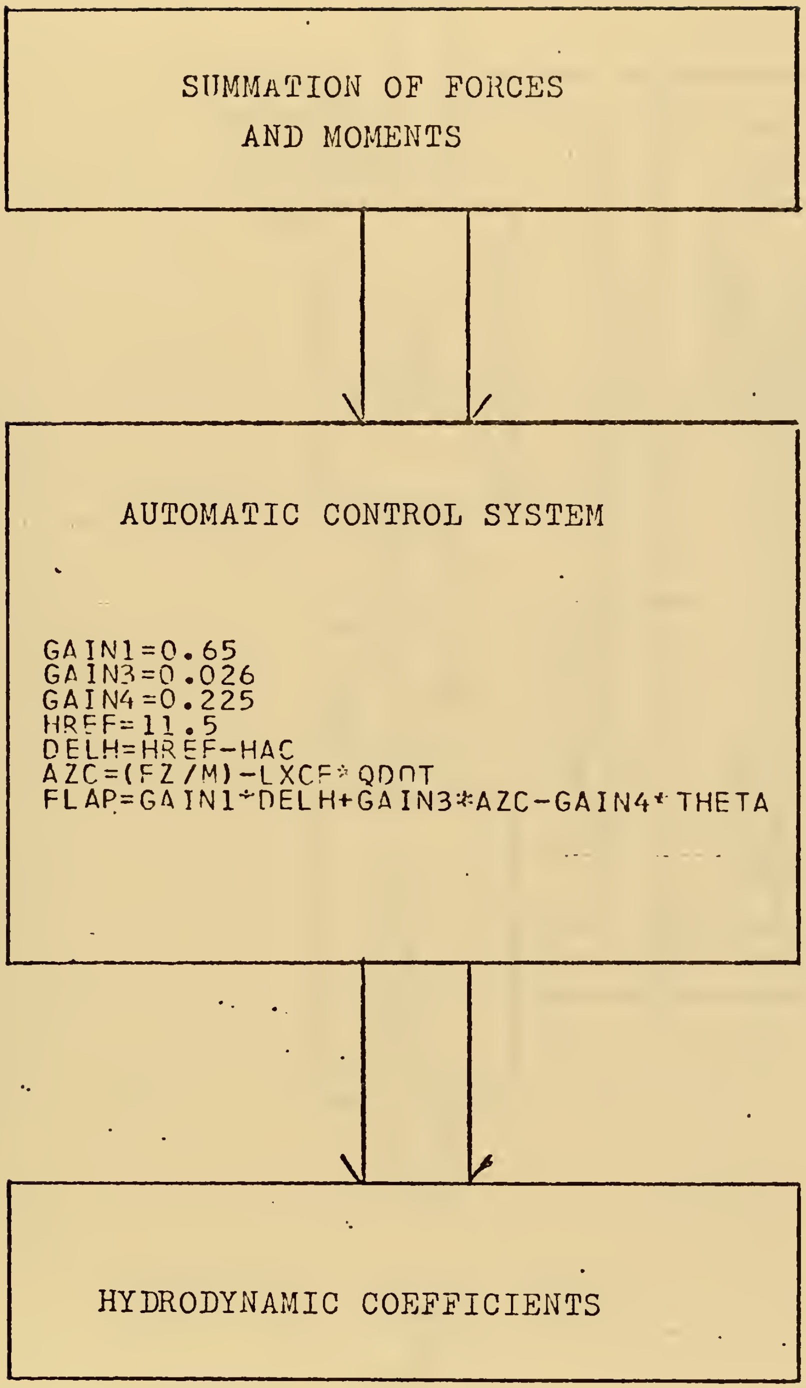


Figure 3- 8 . Automatic Control System With an Accelerometer

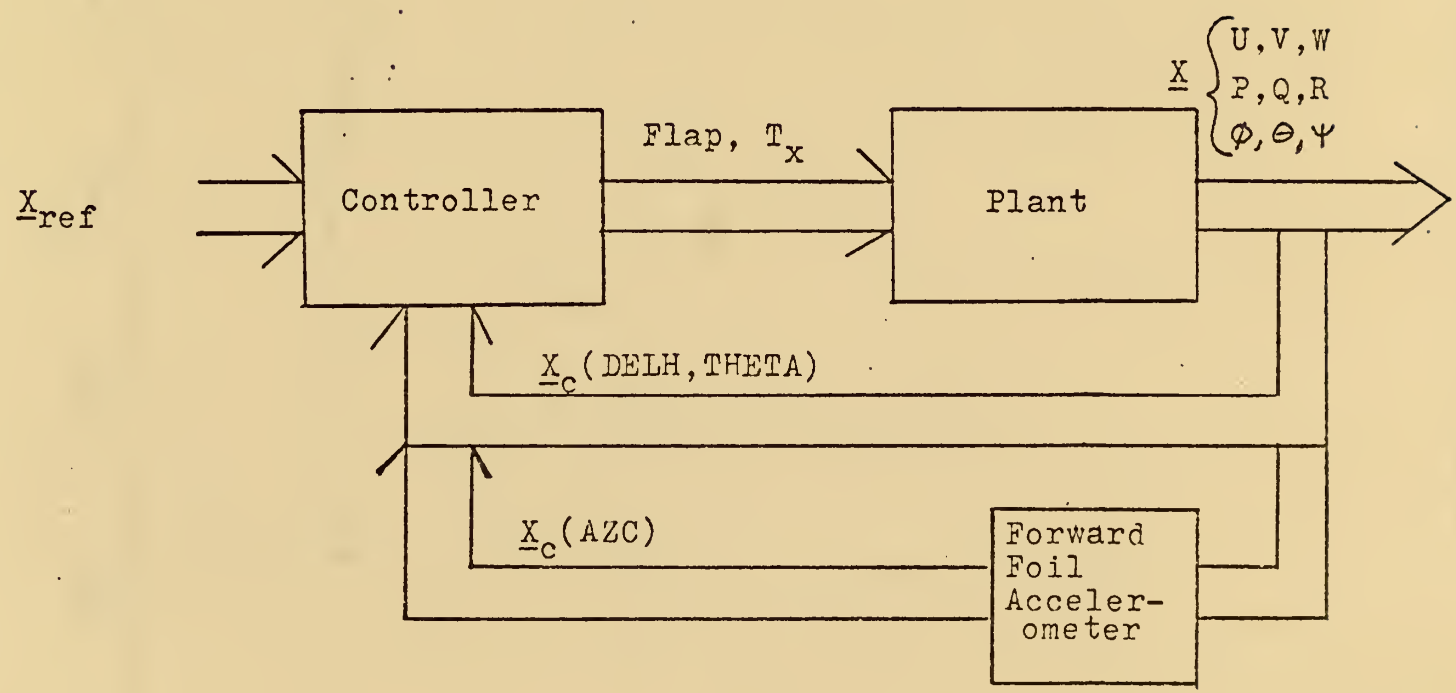
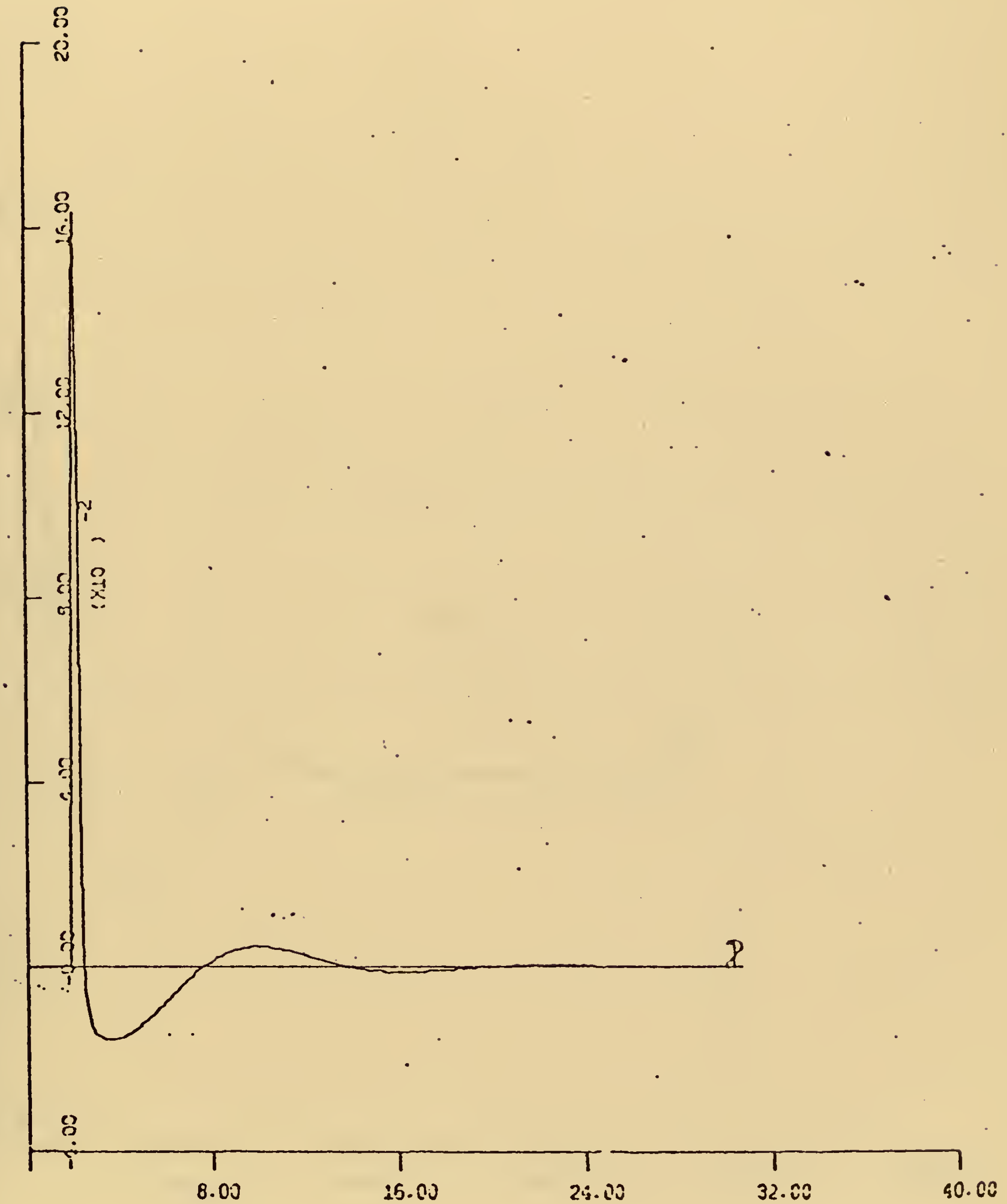


Figure 3-9. Block Diagram Showing Rate Feedhack With an Accelerometer

PITCH RATE VS TIME

Rate Feedback With Accelerometer



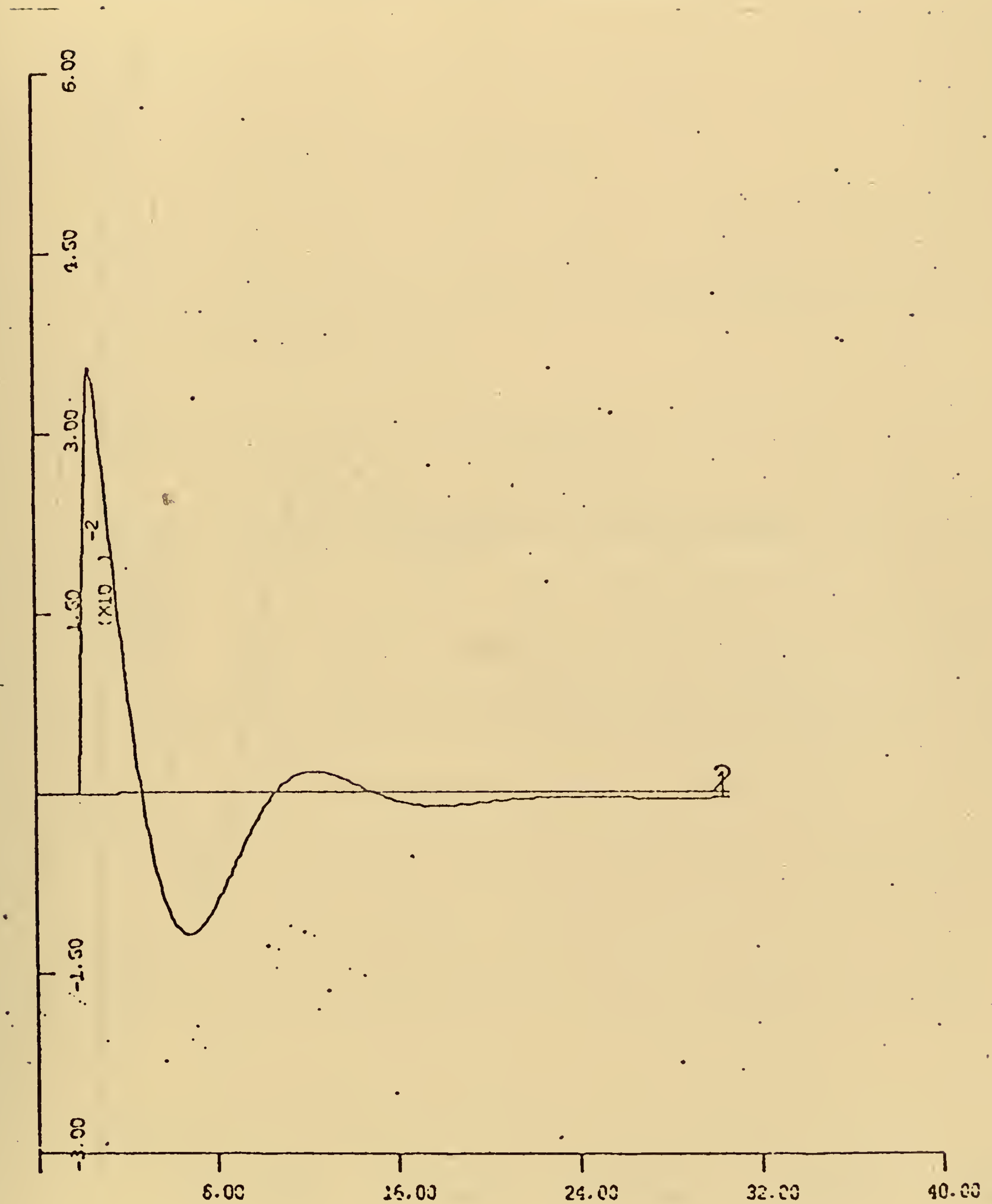
X-Scale = 8 seconds/inch

Y-Scale = 0.04 radians/second

Figure 3-10

PITCH ANGLE VS TIME

Rate Feedback With Accelerometer



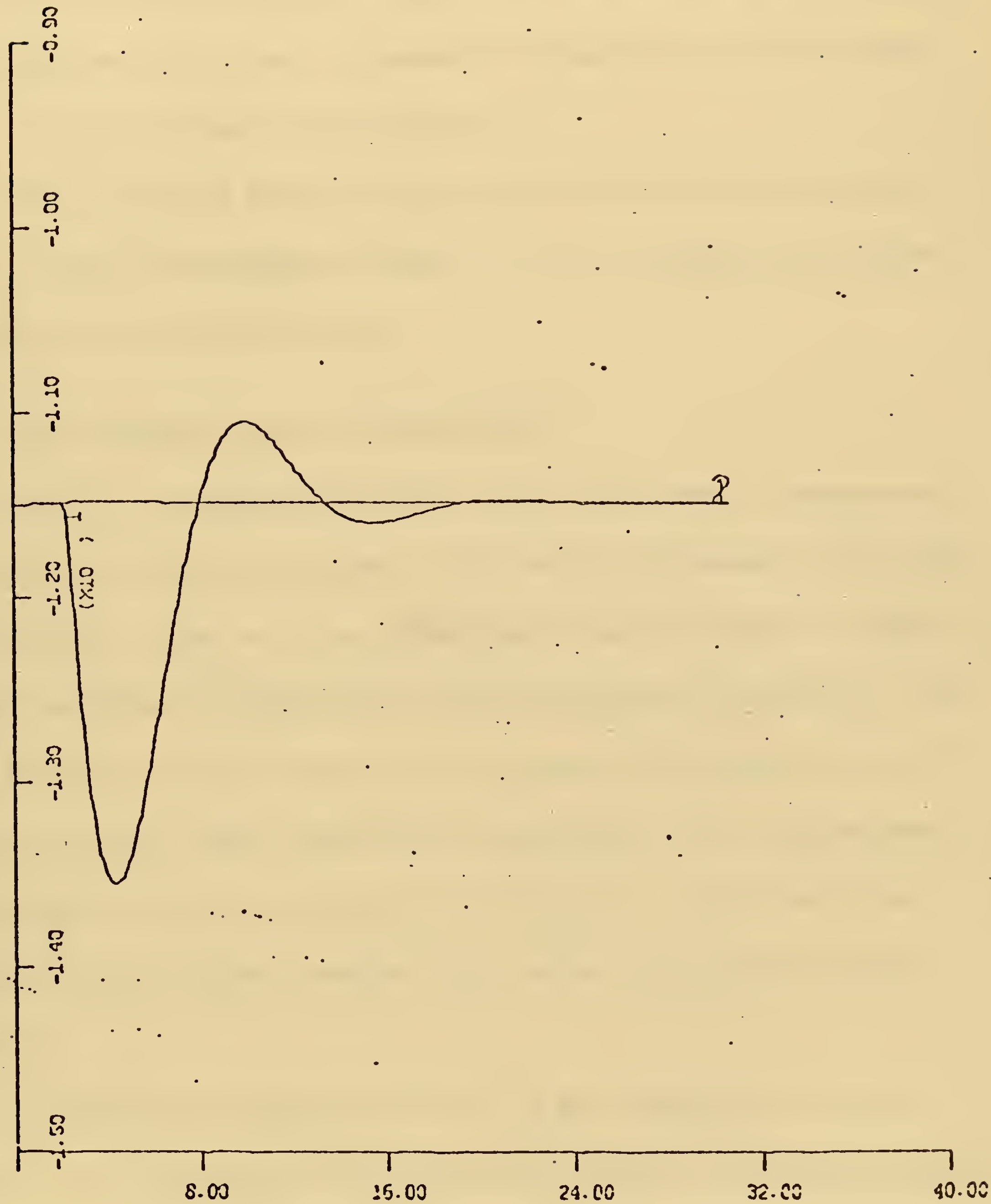
X-Scale = 8 seconds/inch

Y-Scale = 0.02 radians/inch

Figure 3-11

SUBMERGENCE VS TIME

Rate Feedback With Accelerometer



X-Scale = 8 seconds/inch

Y-Scale = 1 foot/inch

Figure 3-12

motion of the flap to lag the motion of the model and thus cause the flap to continue moving after the error had ceased. It was also noted that when the acceleration and pitch angle gain constants became too large, the system went unstable. Comparison of figures 3-13, 14, 15, with 3-10, 11, 12, confirms these statements.

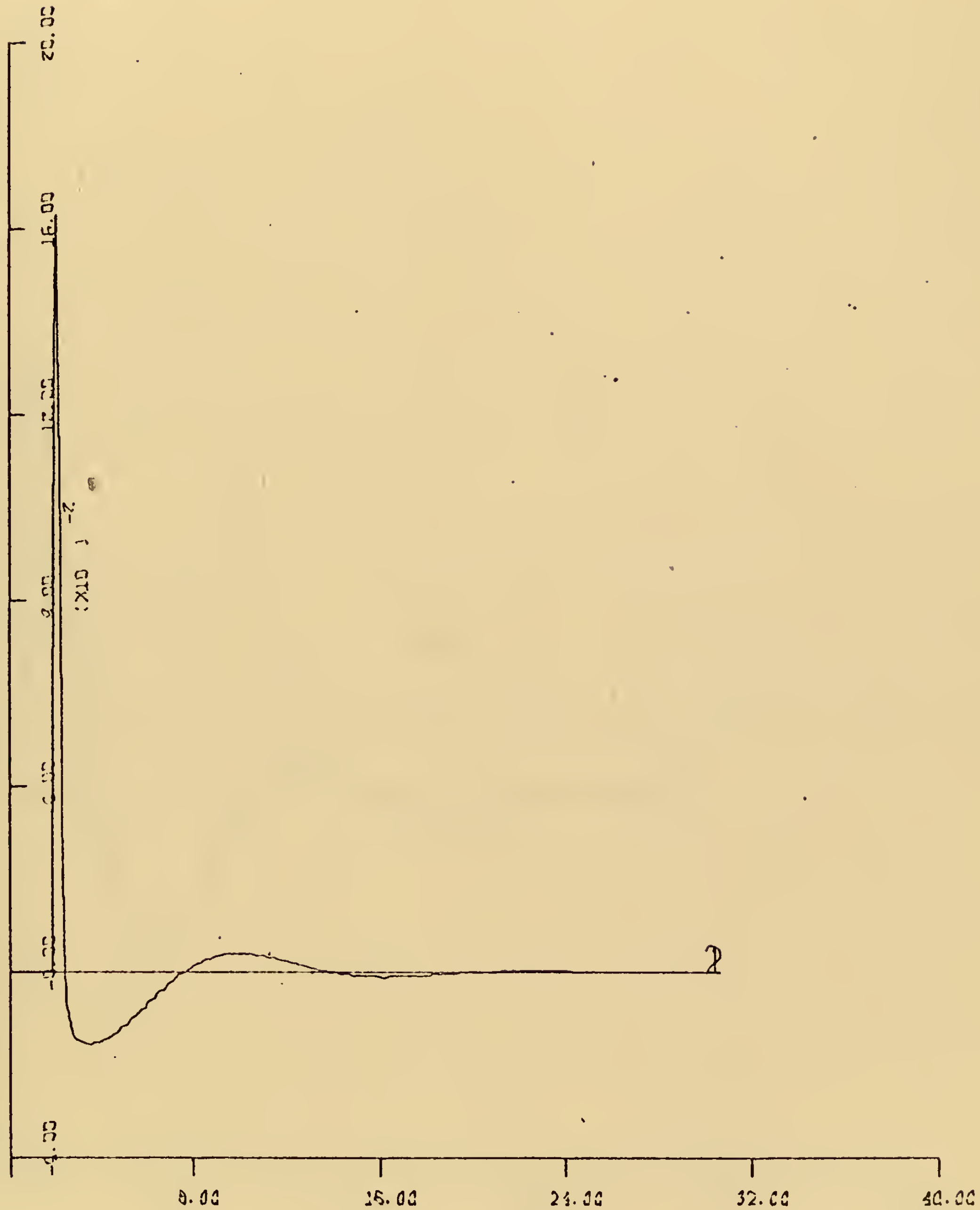
The contents of the automatic control block are shown in figure 3-16. In the block diagram of figure 3-17, the real pole term is incorporated into the controller block.

E. RATE FEEDBACK WITH COMPENSATOR

In order to minimize the effect of the inertia term, a compensator had to be included in the system. The inertia term caused a time lag in the response, therefore, a lead compensator had to be added to make the overall response approximate that of the instantaneous response. The term that was actually inserted was a computer artificiality because it took on the role of both real pole and compensator. The compensator of the simulation takes on the form $(P_1S+1)/(P_2S+1)$. In the root locus, another pole was added, however, it is so far to the left that it was ignored.

Comparison of figures 3-18, 19, 20 with figures 3-10, 11, 12 shows that the compensator did reduce the overshoot and time lag associated with the real pole. Close observation shows that the response of the model with the lead compensator closely approaches the response of the model with an instantaneous flap.

Pitch Rate vs Time
Real Pole Included

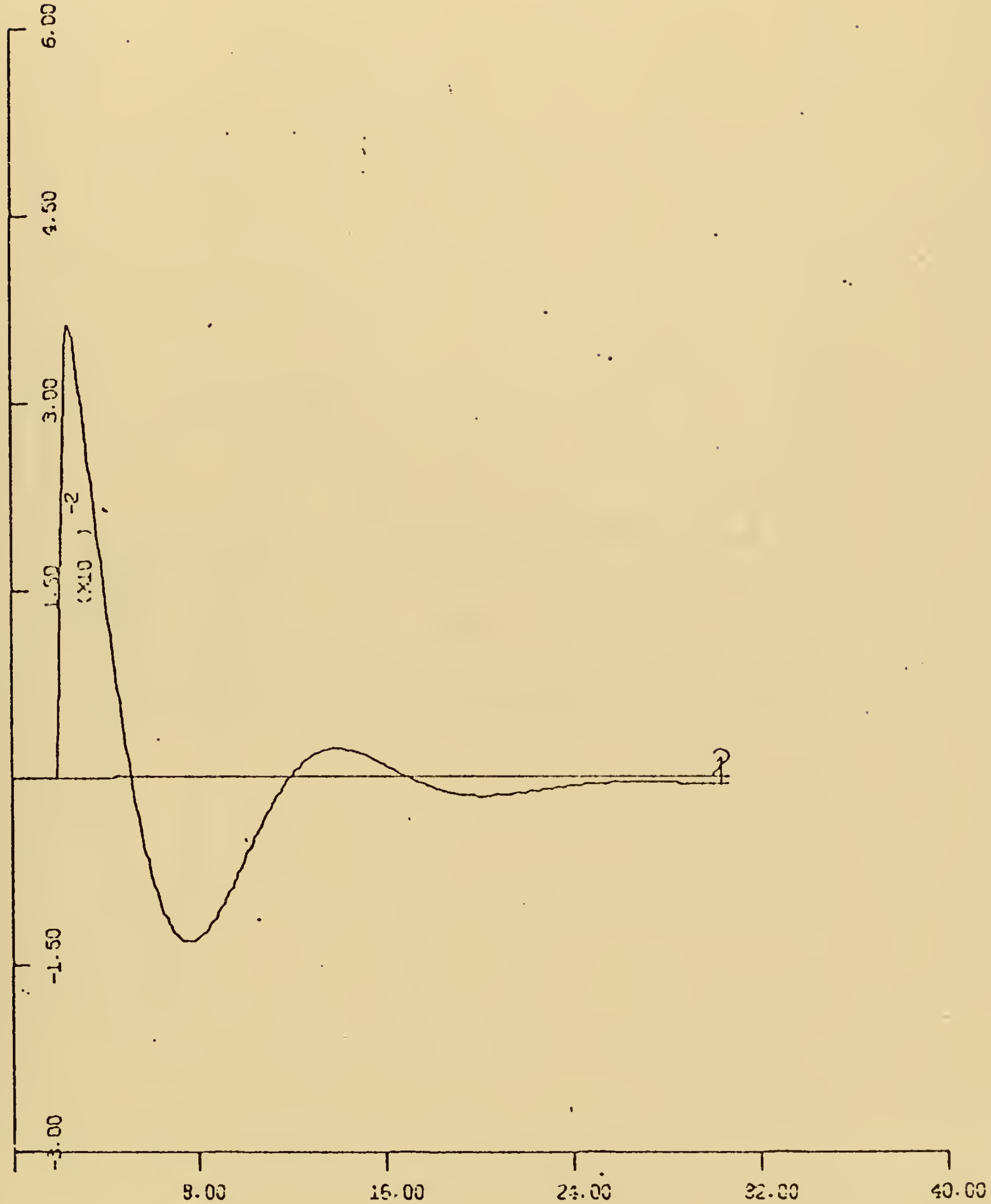


X-Scale = 8 seconds/inch
Y-Scale = 0.04 radians/second

Gain 1 = 0.65
Gain 3 = 0.026
Gain 4 = 0.225

Figure 3-13

Pitch Angle vs Time
Real Pole Included

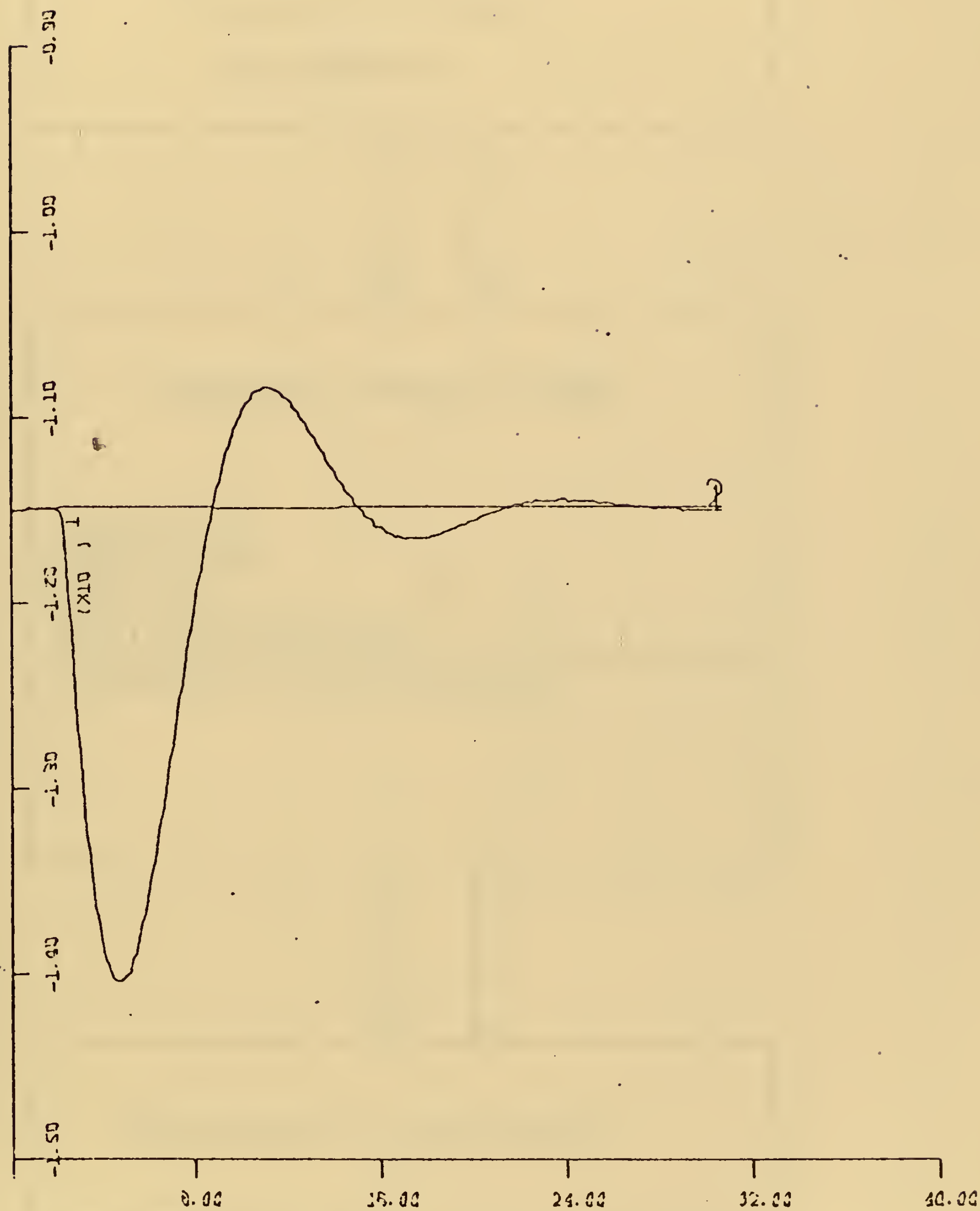


X-Scale = 8 seconds/inch
Y-Scale = 0.02 radians/inch

Gain 1 = 0.65
Gain 3 = 0.026
Gain 4 = 0.225

Figure 3-14

Submergence vs Time
Real Pole Included



X-Scale = 8 seconds/inch

Y-Scale = 1 foot/inch

Gain 1 = 0.65

Gain 3 = 0.026

Gain 4 = 0.225

Figure 3-15

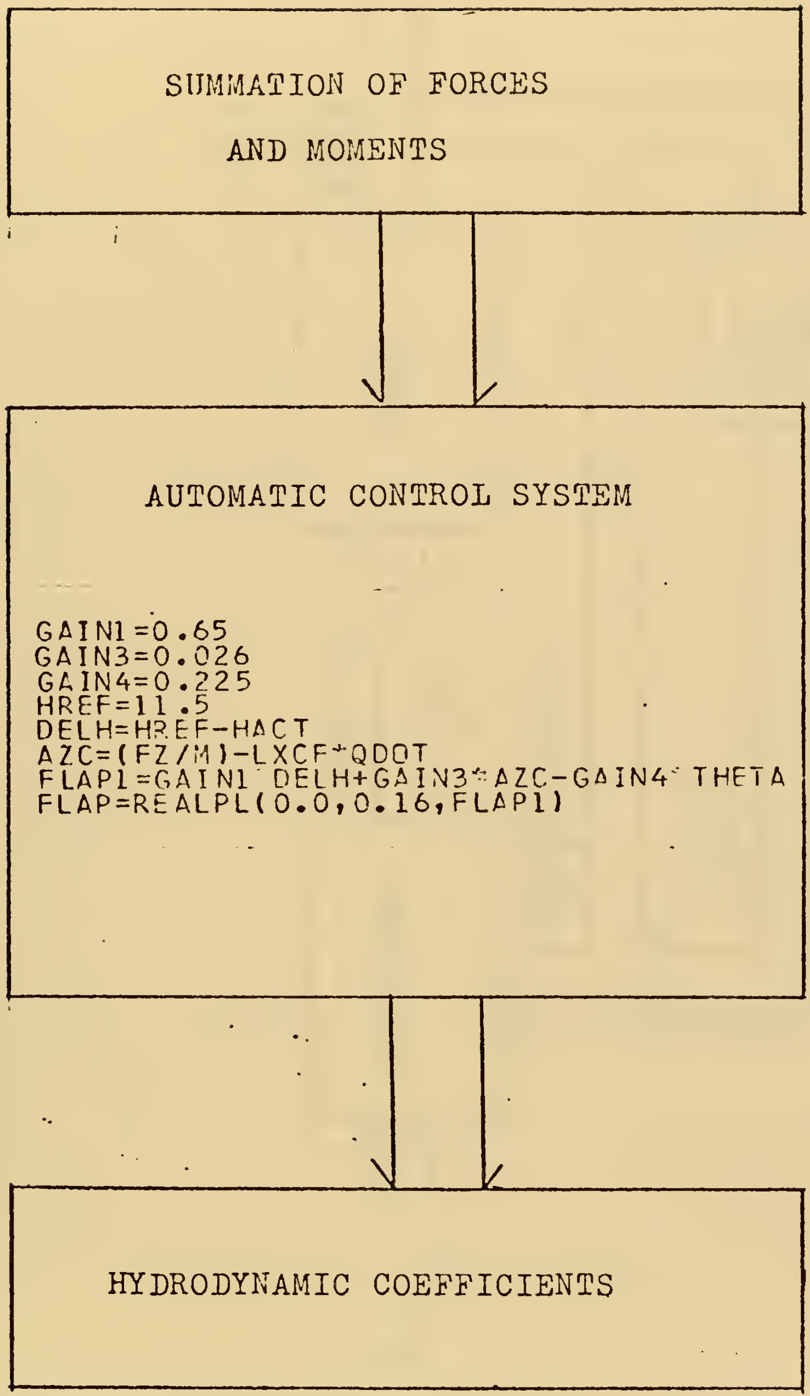


Figure 3-16. Automatic Control System With Inertia Included

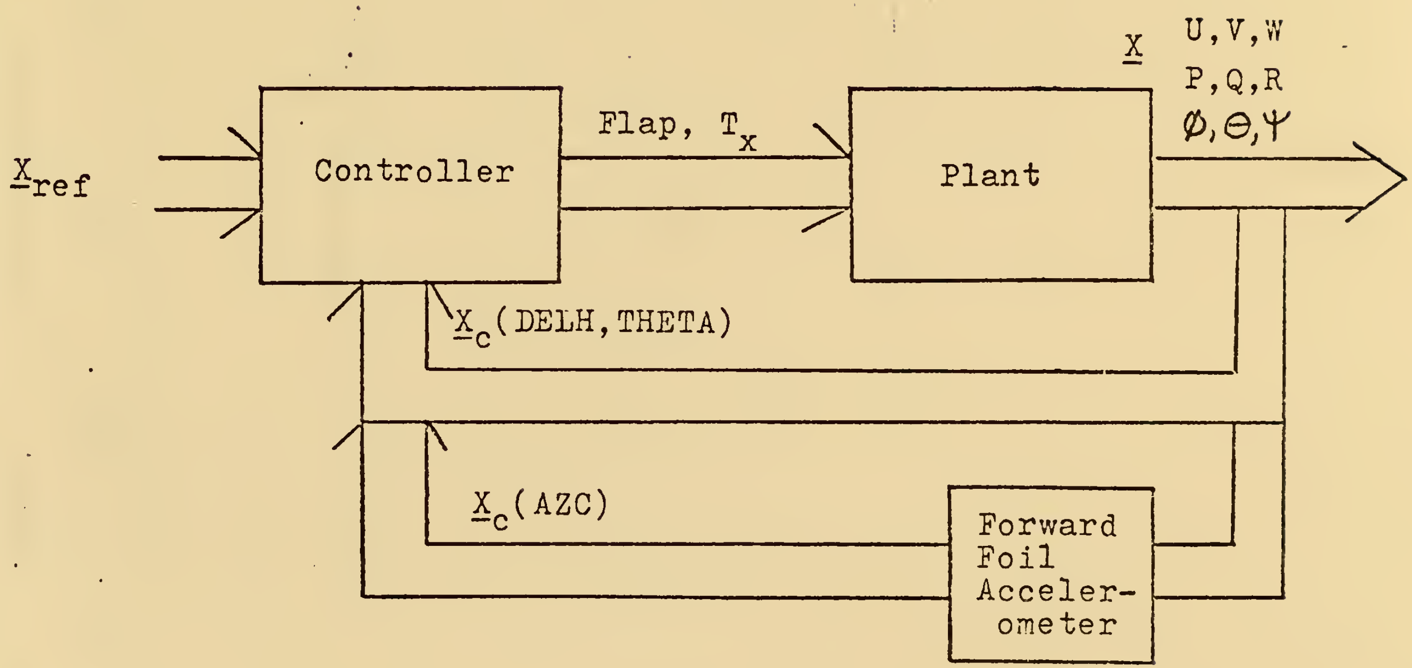
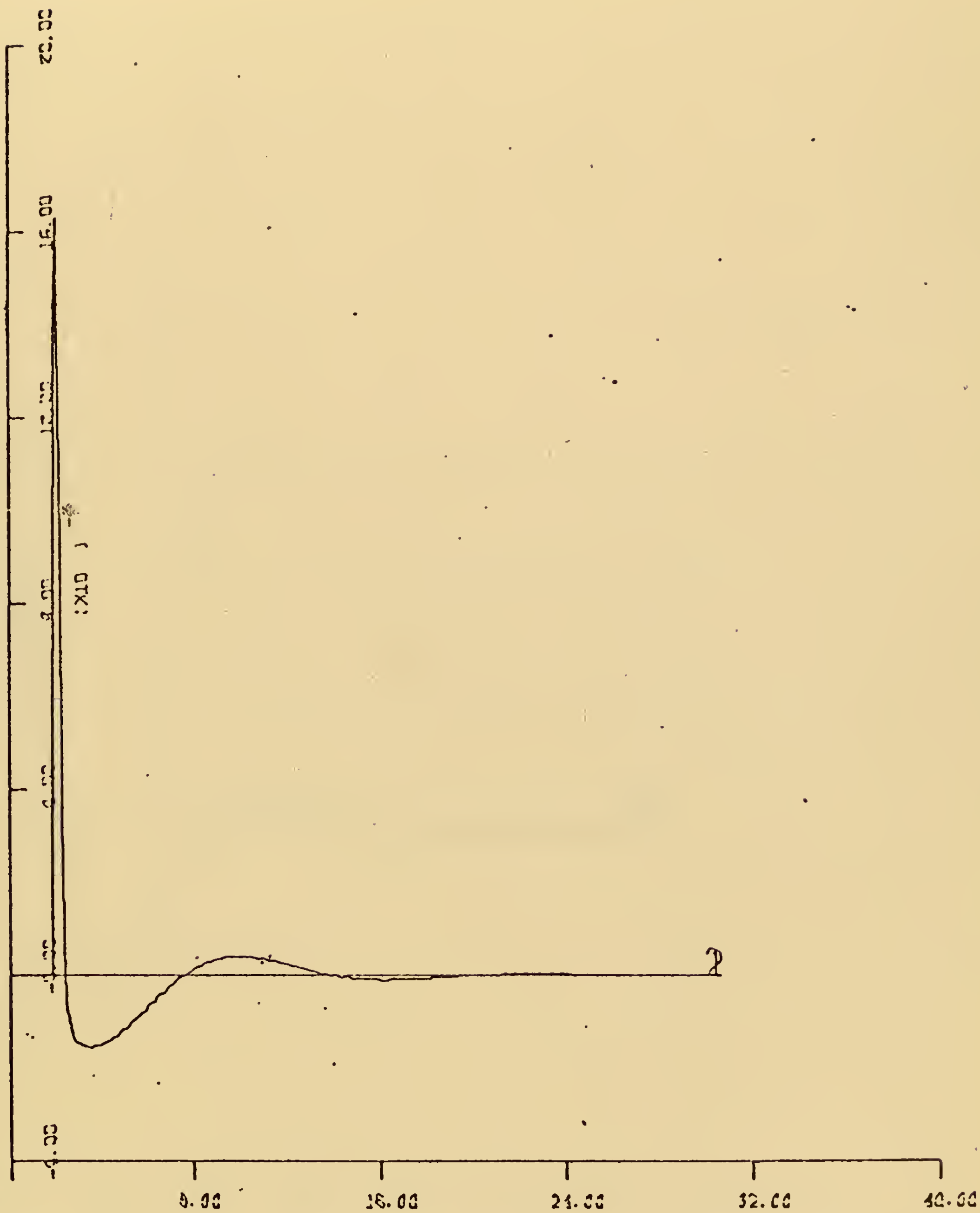


Figure 3-17. Block Diagram Showing System With Inertia Included

PITCH RATE VS TIME

Compensator included



X-Scale = 8 seconds/inch

Y-Scale = 0.04 radians/second

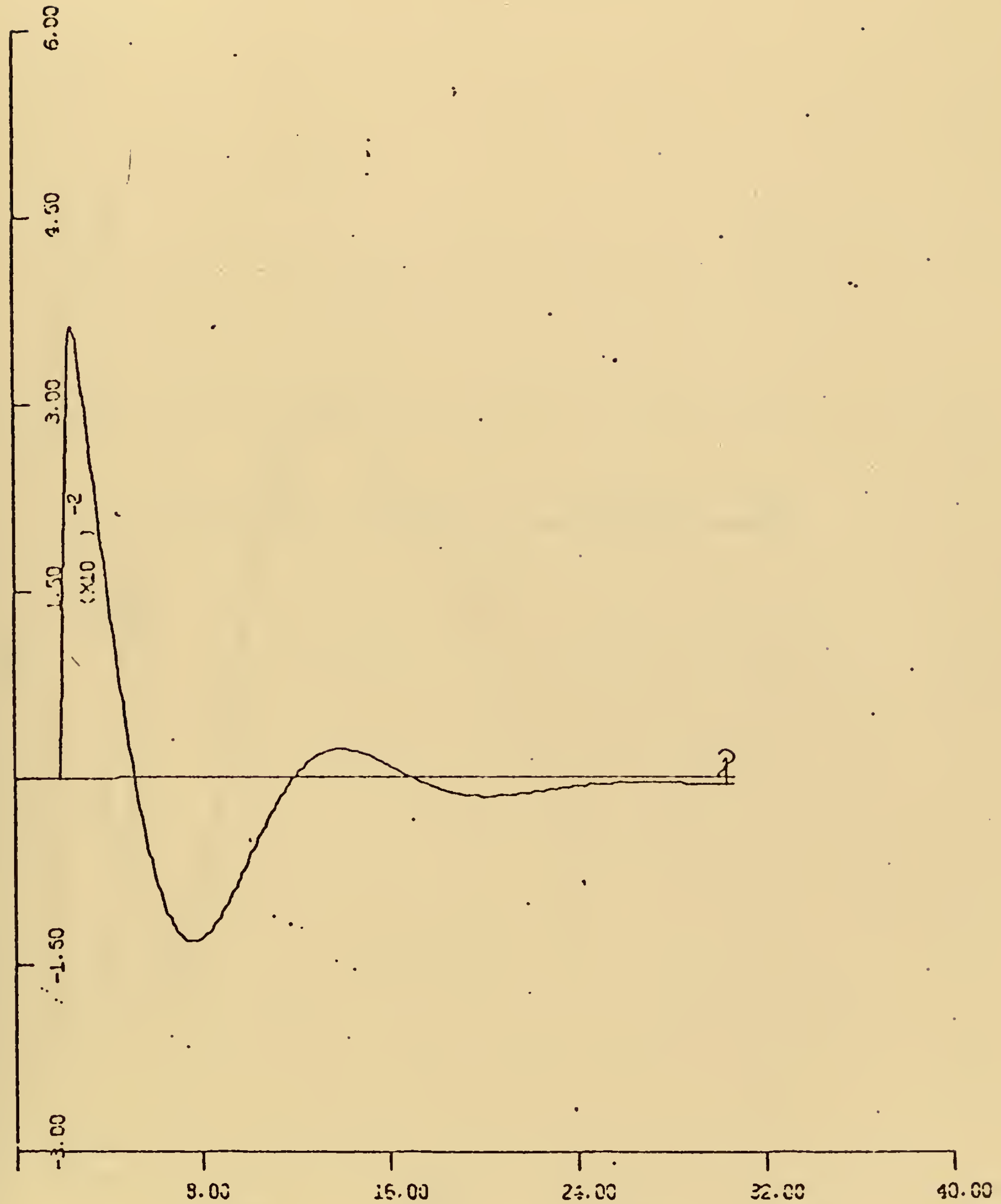
Gain 1 = 0.65

Gain 3 = 0.026

Gain 4 = 0.225

Figure 3-18

PITCH ANGLE VS TIME
Compensator Included

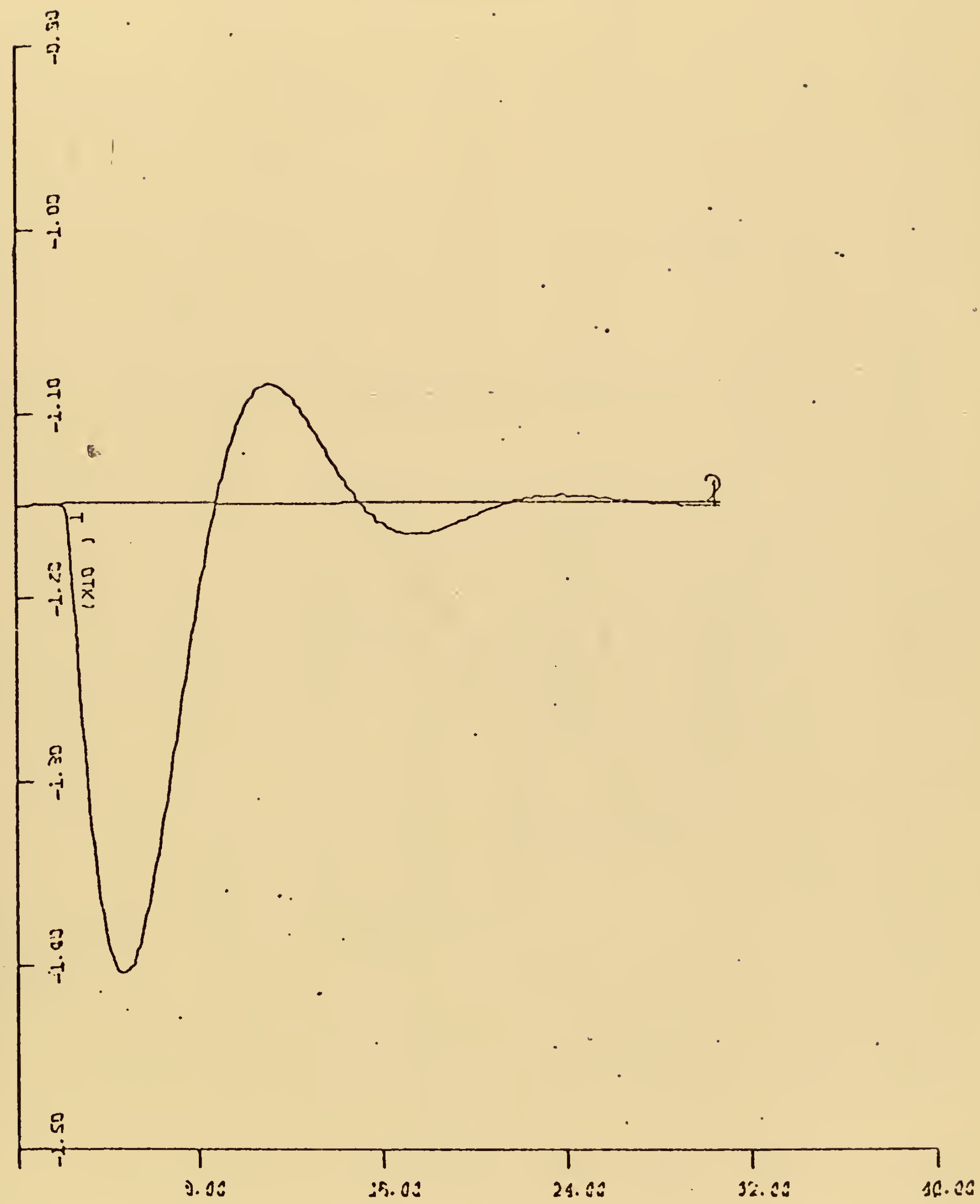


X-Scale = 8 seconds/inch
Y-Scale = 0.02 radians/inch

Gain 1 = 0.65
Gain 3 = 0.026
Gain 4 = 0.225

Figure 3-19

SUBMERGENCE VS TIME
Compensator Included



X-Scale = 8 seconds/inch
Y-Scale = 1 foot/inch

Gain 1 = 0.65
Gain 3 = 0.026
Gain 4 = 0.225

Figure 3-20

The contents of the automatic control block are as shown in the main simulation program in the computer program section. The block diagram for the system is shown in figure 3-21.

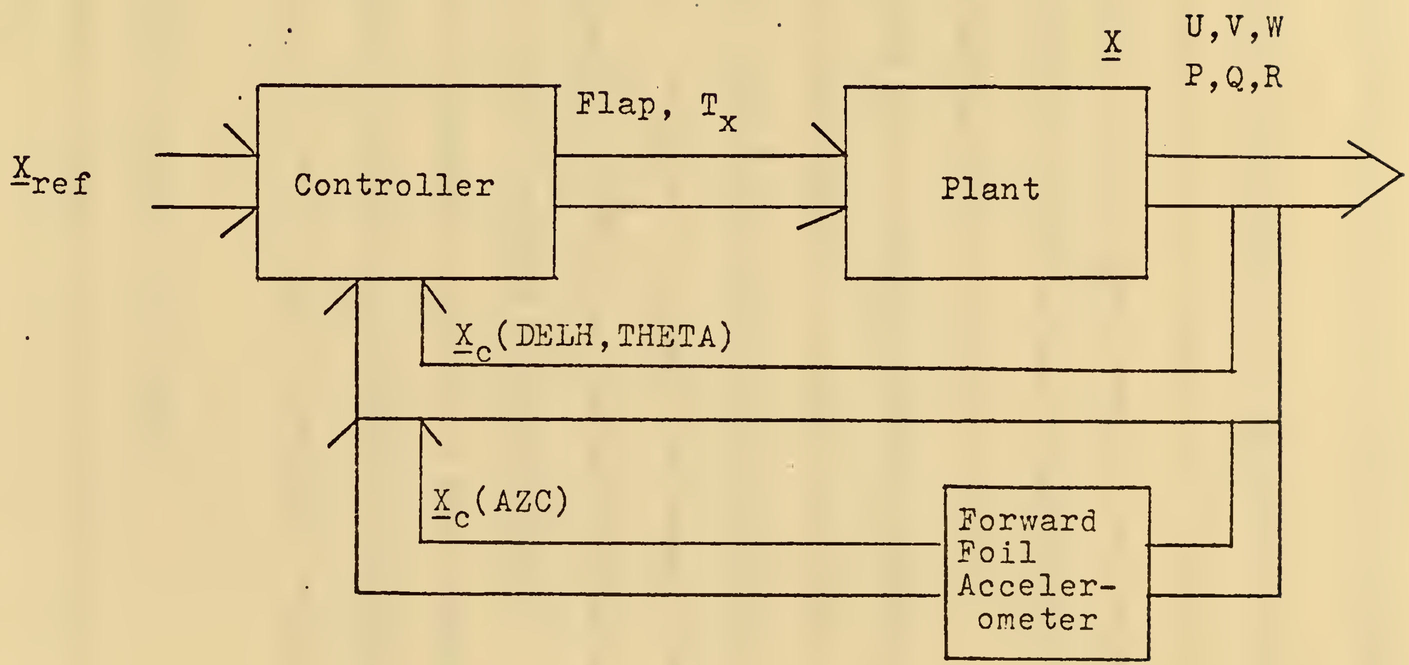


Figure 3-21. Block Diagram for Compensated Control System

III. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

An invalid beginning assumption, i.e. the craft is stable without a control system, caused the loss of a great deal of time early in the research. This was not a complete loss, however, as it necessitated the writing of the ANGLE OF ATTACK program to determine the angles of attack and thrust which balanced the equations of motion.

The data obtained from the ANGLE OF ATTACK program illustrated the tremendous effect slight changes in angle of attack make on the motion of the model. Since these motions are so slight and occur in such short time intervals, it would not be possible for manual control. This necessitates an automatic control system that will provide the necessary outputs to operate the model according to the given inputs.

A stable model was obtained as a result of this research, however, it is somewhat limited. Using the present model and expanding it to include the after foils, the model would be completely stable in six degrees of freedom.

Recommendations for further study include;

1. Incorporate a complete automatic control system which would include all three foils.

2. Produce a simulation for the transition period between hull-borne and foilborne conditions.

3. A study of the step response of the model in all modes.

4. A study of the stability of the model in both regular and random seas.

5. A study of the turning characteristics.

APPENDIX A

SUMMARY OF COMPLETE EQUATIONS

Equations for Accelerations in Body Axes

$$\dot{u} = \frac{1}{m} F_x + RV - QW \tag{A-1}$$

$$\dot{V} = \frac{1}{m} F_y + PW - RU \tag{A-2}$$

$$\dot{W} = \frac{1}{m} F_z + QU - PV \tag{A-3}$$

$$\dot{P} = \frac{1}{I_{xx}} \left[L - QR(I_{zz} - I_{yy}) + (\dot{R} + QP) I_{xz} \right] \tag{A-4}$$

$$\dot{Q} = \frac{1}{I_{yy}} \left[M - RP(I_{xx} - I_{zz}) - (\dot{P} - R^2) I_{xz} \right] \tag{A-5}$$

$$\dot{R} = \frac{1}{I_{zz}} \left[N - PQ(I_{yy} - I_{xx}) - (QR - \dot{P}) I_{xz} \right] \tag{A-6}$$

Velocities in Body Axes

$$U = \int \dot{u}\, dt \tag{A-7}$$

$$V = \int \dot{V}\, dt \tag{A-8}$$

$$W = \int \dot{W}\, dt \tag{A-9}$$

$$P = \int \dot{P}\, dt \tag{A-10}$$

$$Q = \int \dot{Q}\, dt \tag{A-11}$$

$$R = \int \dot{R}\, dt \tag{A-12}$$

Transformation of Velocities from Body to Earth Axes

$$U_E = U\cos\Theta\cos\Psi + V(\cos\Psi\sin\Theta\sin\phi - \sin\Psi\cos\phi)$$

$$+ W(\cos\Psi\sin\Theta\cos\phi + \sin\Psi\sin\phi) \quad \text{(A-13)}$$

$$V_E = U\cos\Theta\sin\Psi + V(\cos\Psi\cos\phi + \sin\Psi\sin\Theta\sin\phi)$$

$$+ W(\sin\Psi\sin\Theta\cos\phi - \cos\Psi\sin\phi) \quad \text{(A-14)}$$

$$W_E = -U\sin\Theta + V\cos\Theta\sin\phi + W\cos\Theta\cos\phi \quad \text{(A-15)}$$

$$\dot{\phi} = P + \dot{\Psi}\sin\Theta \quad \text{(A-16)}$$

$$\dot{\Theta} = Q\cos\phi - R\sin\phi \quad \text{(A-17)}$$

$$\dot{\Psi} = (Q\sin\phi + R\cos\phi)\cos\Theta + (\dot{\phi} - P)\sin\Theta \quad \text{(A-18)}$$

Positions in Earth Axes

$$X_E = \int U_E\, dt \quad \text{(A-19)}$$

$$Y_E = \int V_E\, dt \quad \text{(A-20)}$$

$$Z_E = \int W_E\, dt \quad \text{(A-21)}$$

$$\phi = \int \dot{\phi}\, dt \quad \text{(A-22)}$$

$$\Theta = \int \dot{\Theta}\, dt \quad \text{(A-23)}$$

$$\Psi = \int \dot{\Psi}\, dt \quad \text{(A-24)}$$

Expansion of Force and Moment Equations

$$F_X = \sum F_{XiF} + \sum F_{Xis} + mg_X + T_X \tag{A-25}$$

$$F_Y = \sum F_{Yis} + mg_Y \tag{A-26}$$

$$F_Z = \sum F_{ZiF} + mg_Z \tag{A-27}$$

$$L = (F_Z L_Y)_{PF} + (F_Z L_Y)_{SF} - (F_Y L_Z)_{PS} - (F_Y L_Z)_{SS} - (F_Y L_Z)_{CS} \tag{A-28}$$

$$M = \sum (F_Z L_X)_{iF} + \sum (F_X L_Z)_{iF} + \sum (F_X L_Z)_{iS} + T_X L_{ZT} \tag{A-29}$$

$$N = \sum (F_Y L_X)_{iS} \tag{A-30}$$

Expansion of Gravity Terms

$$mg_X = -mg \sin\theta \tag{A-31}$$

$$mg_Y = mg \cos\theta \sin\phi \tag{A-32}$$

$$mg_Z = mg \cos\theta \cos\phi \tag{A-33}$$

Foil Velocity Components in Body Axes

Center Foil-

$$U_C = U + L_{ZCF} Q \tag{A-34}$$

$$V_C = V - L_{ZCF} P + L_{XCF} R \tag{A-35}$$

$$W_C = W - L_{XCF} Q \tag{A-36}$$

Port Foil-

$$U_P = U + L_{ZPF} Q - L_{YPF} R \tag{A-37}$$

$$V_P = V - L_{ZPF} P + L_{XPF} R \tag{A-38}$$

$$W_P = W + L_{YPF} P - L_{XPF} Q \tag{A-39}$$

Starboard Foil-

$$U_S = U + L_{ZSF} Q - L_{YSF} R \tag{A-40}$$

$$V_S = V - L_{ZSF} P + L_{XSF} R \tag{A-41}$$

$$W_S = W + L_{YSF} P - L_{XSF} Q \tag{A-42}$$

Mid Foil-

$$U_M = U + L_{ZMF} Q \tag{A-43}$$

$$V_M = V - L_{ZMF} P + L_{XMF} R \tag{A-44}$$

$$W_M = W - L_{XMF} Q \tag{A-45}$$

<u>Transformation of Water Particle Orbital Velocity from Earth to Body Axes</u>

$$U_{Wi} = U_{EWi} \cos\psi \cos\theta + V_{EWi} \sin\psi \cos\theta - W_{EWi} \sin\theta \tag{A-46}$$

$$V_{Wi} = U_{EWi}(\cos\psi \sin\theta \sin\phi - \sin\psi \cos\phi) + V_{EWi}(\sin\psi \sin\theta \sin\phi + \cos\psi \cos\phi) + W_{EWi} \cos\theta \sin\phi \tag{A-47}$$

$$W_{wi} = U_{EWi}(\cos\Psi \sin\theta \cos\phi + \sin\Psi \sin\phi) + V_{EWi}(\sin\Psi \sin\theta \cos\phi - \cos\Psi \sin\phi) + W_{EWi} \cos\theta \cos\phi \quad \text{(A-48)}$$

Each of these equations must be repeated for each foil.

Relative Velocity Components

$$U_{ri} = U_i - U_{wi} \quad \text{(A-49)}$$

$$V_{ri} = V_i - V_{wi} \quad \text{(A-50)}$$

$$W_{ri} = W_i - W_{wi} \quad \text{(A-51)}$$

One set of equations for each foil.

Angles of Attack and Side Slip

$$\alpha_i = \text{ARCTAN } W_{ri}/U_{ri} + \alpha_{i\text{-fixed}} \quad \text{(A-52)*}$$

$$\beta_i = \text{ARCSIN } \frac{V_{ri}}{\sqrt{U_{ri}^2 + V_{ri}^2 + W_{ri}^2}} \quad \text{(A-53)*}$$

Total Relative Velocity at a Particular Foil or Strut

$$\mathcal{V} = \sqrt{U_r^2 + V_r^2 + W_r^2} \quad \text{(A-54)}$$

* One set of equations for each foil. Angles of attack and side slip are calculated in radians.

Hydrodynamic Forces in Water Axes

(Each foil equation and strut equation must be repeated for each foil and strut, respectively)

Foil Lift

$$F_L = \frac{1}{2} \rho \mathcal{V}^2 A_F C_F \tag{A-55}$$

Foil Drag

$$F_{DF} = \frac{1}{2} \rho \mathcal{V}^2 A_F C_{DF} \tag{A-56}$$

Strut Drag

$$F_{DS} = \frac{1}{2} \rho \mathcal{V}^2 A_S C_{DS} \tag{A-57}$$

Strut Side Force

$$F_S = \frac{1}{2} \rho \mathcal{V}^2 A_S C_S \tag{A-58}$$

Transformation of Foil Forces from Water Axes to Body Axes

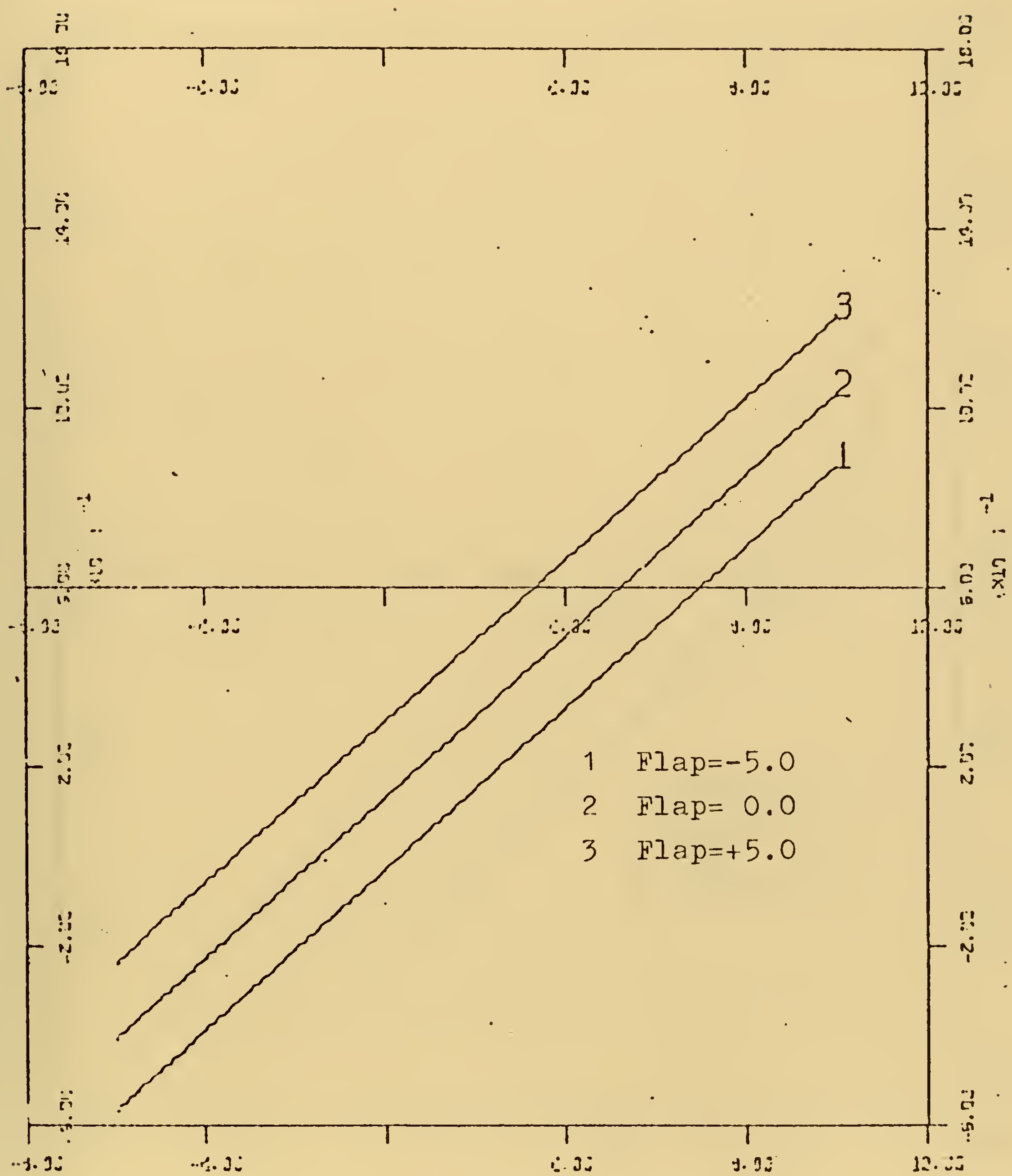
$$F_{XiF} = -F_{DiF} \cos\alpha \cos\beta + F_{LiF} \sin\alpha \tag{A-59}$$

$$F_{YiF} = -F_{DiF} \sin\beta \tag{-60}$$

$$F_{ZiF} = -F_{DiF} \sin\alpha \cos\beta - F_{LiF} \cos\alpha \tag{A-61}$$

APPENDIX B

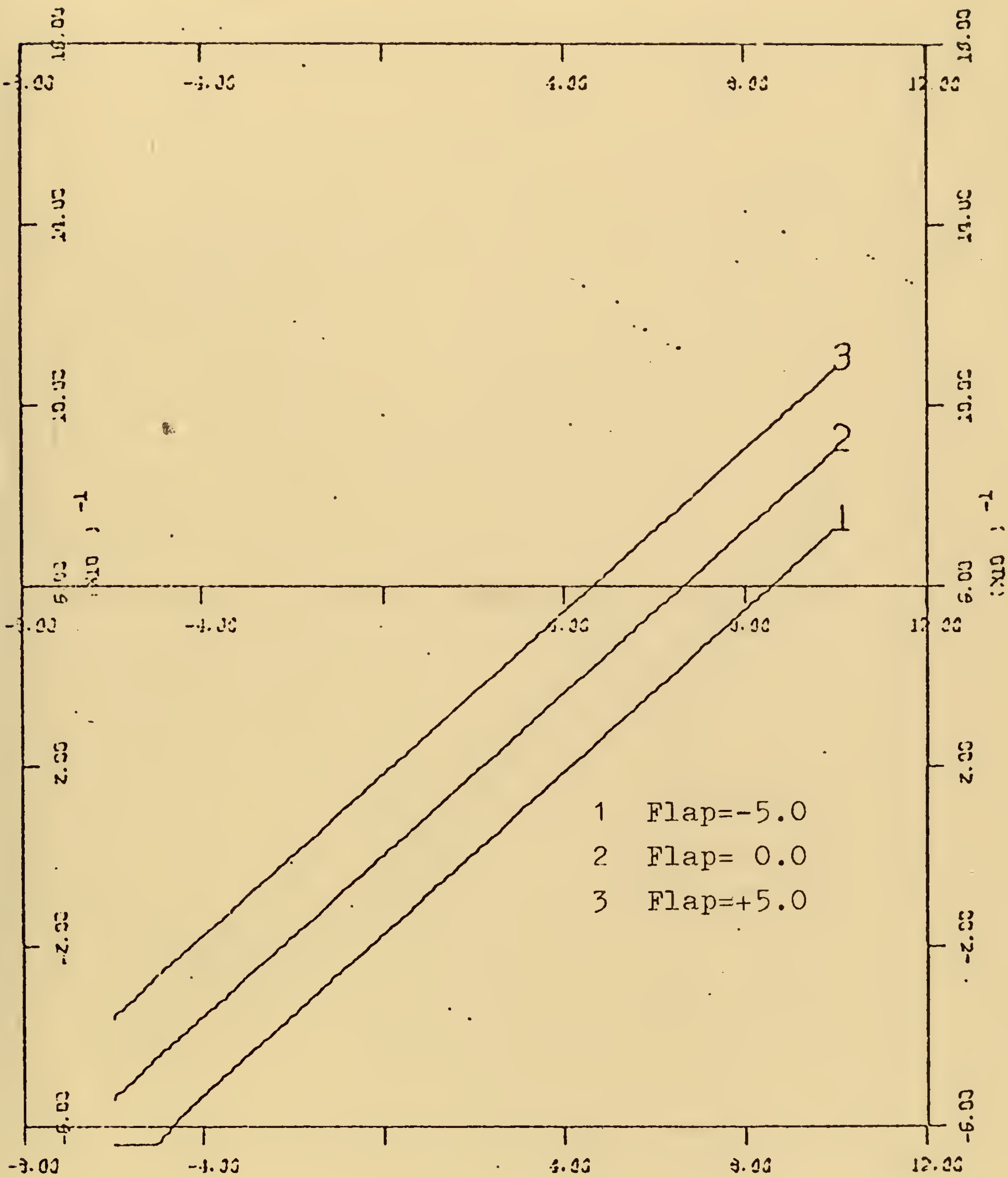
Fwd Foil Lift Coefficient vs Angle of Attack



X Scale = 4.0 degrees/inch

Y Scale = 0.40 units/inch

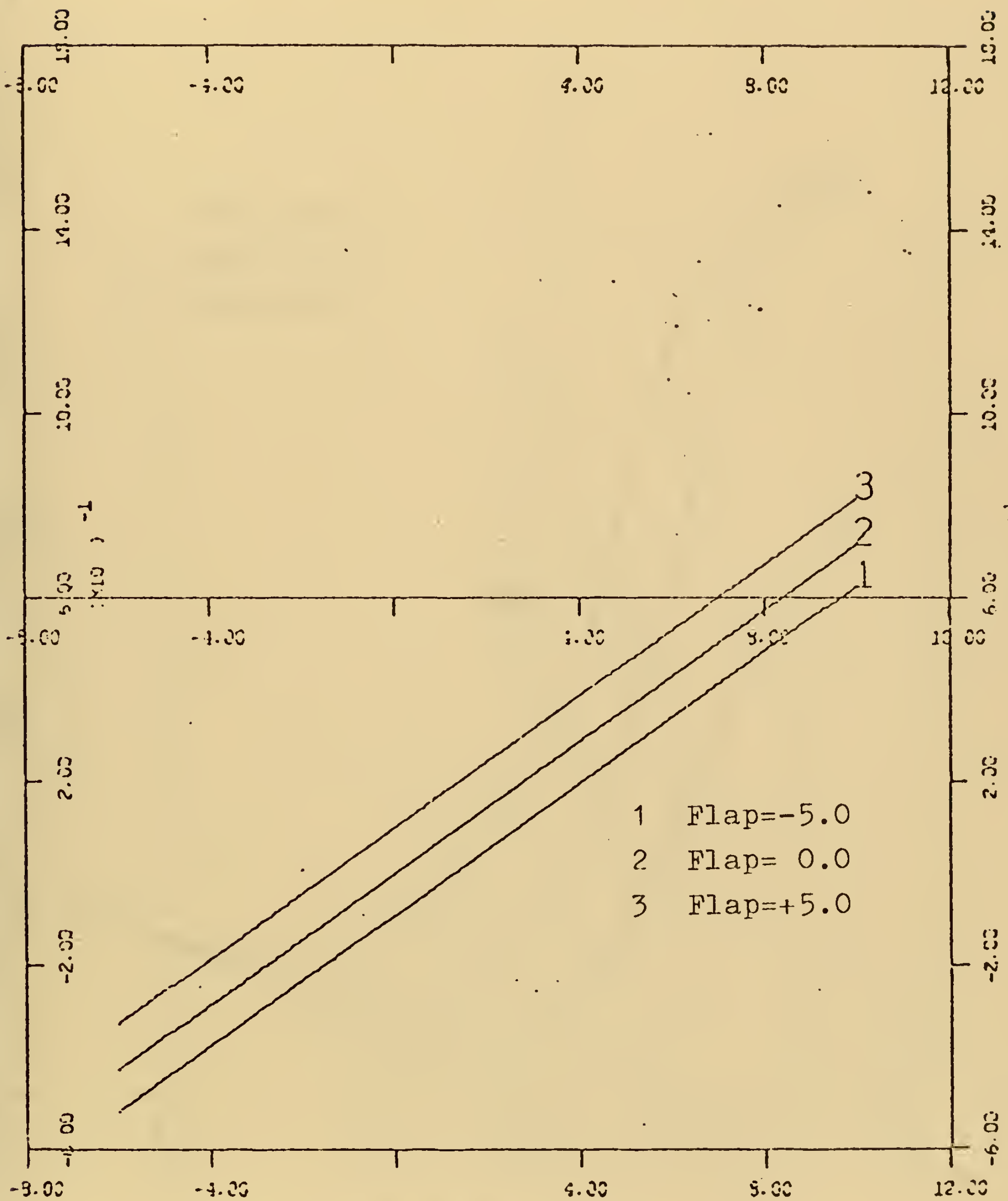
Mid Foil Lift Coefficient vs time



X Scale = 4.0 degrees/inch

Y Scale = 0.40 units/inch

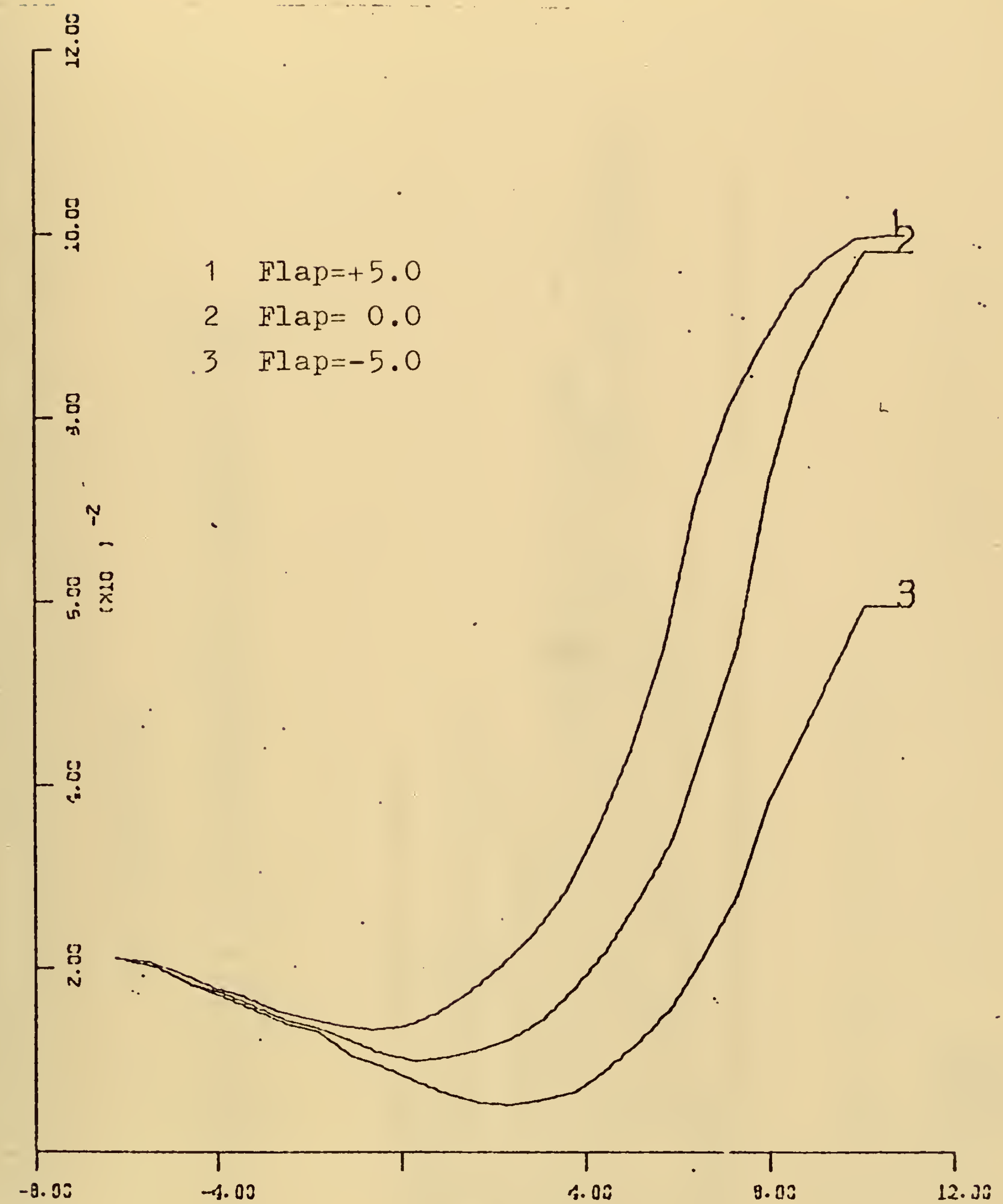
Aft Foil Lift Coefficient vs Angle of Attack



X Scale = 4.0 degrees/inch

Y Scale = 0.40 units/inch

Fwd Foil Drag Coefficient vs Angle of Attack



X Scale = 4.0 degrees/inch

Y Scale = 0.02 units/inch

```
 MAIN SIMULATION

      THIS PROGRAM IS A SIMULATION OF THE U.S. NAVY HYDROFOIL
      HIGH POINT PC(H)-1.  THIS SIMULATION IS ONLY VALID FOR
      THE FOILBORNE MODE OF OPERATION AND IS LIMITED TO THE
      PITCH-HEAVE-SURGE MODE.


// EXEC DSL,PARM.C='NOSOURCE,NOMAP'
//DSL.INPUT DD *
D      COMMON MATRIX(539)
CONTRL FINTIM=30.0, DELT=0.05,DELS=0.1
INTEG RKSFX
INTGER IFLAG,IFLAG1,NPLOT,NUM,NCUR
CONST NPLOT=5, NCUR=1,IFLAG=0
CONST WEIGHT=262527, IXX=601200, IYY=4286000, IZZ=4174000, G=32.2
CONST ACF=65.4, APF=36.8, ASF=36.8, AMF=76.0,PI=3.141593
CONST LXCF=41.59, LXCS=41.59, LXPF=-16.98, LXPS=-16.98, LXSF=-16.98,...
LXSS=-16.98, LXMF=-16.98,LYPF=-12.42, LYPS=-3.0, LYSF=12.42, LYSS=8.0...
,LZCF=15.5, LZCS=13.25, LZPF=17.14, LZPS=14.0, LZSF=17.14,LZSS=14.0,...
LZMF=17.14, LXT=-16.9, LZT=17.7, LXH=68.0
CONST GAIN1=0.65, GAIN3=0.02,GAIN4=0.22,GAINC=1.0
PARAM UZERO=36.0
PREPAR .1,FX,FY,FZ,L,M,N,U,V,W,ZE,P,Q,R,THETA ,UDOT,WDOT,QDOT,ALFAC
*
INITIAL
*
      NUM=0
      DENSE=2.0
      UINIT=UZERO*2000.0*3.0*1.0/3600.0
      U=UINIT
      TX=3960.0
      ALF=0.037111
      ALP=0.074269
      ALS=0.074269
      ALM=0.074269
      HREF=11.5
      FLAX=0.0
      MASS=WEIGHT/G
      CONV=PI/180.0
      FLAP=0.0
      FLAG=0.0
```

```
      IFLAG1=0
      EPS=25.0
      IF(IFLAG.EQ.0) CALL SETUP(FLAG)
      IFLAG=1
      IF(FLAG.EQ.1) CALL ENDRUN
*
DERIVATIVE
*
NOSORT
*
*     ANGLES OF ATTACK AND SIDE SLIP
*
      VRC=V-LZCF*P+LXCF*R
      VRS=V-LZSF*P+LXSF*R
      VRM=V
      VRP=V-LZPF*P+LXPF*R
      WRP=W+LYPF*P-LXPF*Q
      WRS=W+LYSF*P-LXSF*Q
      WRM=W-LXMF*Q
      WRC=W-LXCF*Q
      ALFAC=WRC/U+ALF
      ALFAP=WRP/U+ALP
      ALFAS=WRS/U+ALS
      ALFAM=WRM/U+ALM
      BETAC=VRC/U
      BETAP=VRP/U
      BETAS=VRS/U
*
*     CALCULATION OF EULER ANGLES
*
      PHID1=P
      THETD1=Q
      PSID1=R
*
SORT
*
      PHI=INTGRL(0.0,PHID1)
      THETA=INTGRL(0.0,THETD1)
      PSI=INTGRL(0.0,PSID1)
      WE=-U*SIN(THETA)+V*COS(THETA)*SIN(PHI)+W*COS(THETA)*COS(PHI)
      ZE=INTGRL(-11.5,WE)
*
NOSORT
*
*     WAVE BLOCK
*
      URC=U+LZCF*Q-VEWC*SIN(PSI)
      URP=U+LZPF*Q-LYPF*R-VEWP*SIN(PSI)
```

```
      URS=U+LZSF*Q-LYSF*R-VEWS*SIN(PSI)
      URM=U+LZMF*Q-VEWM*SIN(PSI)
*
*     SUBMERGENCE TERMS
*
      SECF=ZE-LXCF*THETA+LZCF*COS(PHI)
      SEPF=ZE-LXPF*THETA+LYPF*SIN(PHI)+LZPF*COS(PHI)
      SESF=ZE-LXSF*THETA+LYSF*SIN(PHI)+LZSF*COS(PHI)
      SEMF=ZE-LXMF*THETA+LZMF*COS(PHI)
*
*     HYDRODYNAMIC COEFFICIENTS
*
      FLAD=FLAP*CONV
      FDEG=LIMIT(-5.0,5.0,FLAD)
      CALL INTERP(ALFAC,FDEG,COEFCX,2)
      CALL INTERP(ALFAP,FLAX,COEFPX,3)
      CALL INTERP(ALFAS,FLAX,COEFSX,3)
      CALL INTERP(ALFAM,FLAX,COEFMX,1)
      CALL INTRP1(BETAC,SECF,CFDS,2,THETA,THETA1)
      CALL INTRP1(BETAP,SEPF,CPDS,1,THETA,THETA1)
      CALL INTRP1(BETAS,SESF,CSDS,1,THETA,THETA1)
*
*     FORCES IN THE WATER AXES
*
      FGRAX=-MASS*G*SIN(THETA)
      FGRAY=MASS*G*SIN(PHI)
      FGRAZ=MASS*G*COS(PHI)
      CCS=-2.15*BETAC
      ACCS=CCS*4.25*SECF
      FSC=0.5*DENSE*(U**2)*ACCS
      FDSC=0.5*DENSE*(U**2)*CFDS
      PCS=-2.15*BETAP
      APCS=PCS*4.25*SEPF
      FPS=0.5*DENSE*(U**2)*APCS
      FDPS=0.5*DENSE*(U**2)*CPDS
      SCS=-2.15*BETAS
      ASCS=SCS*4.25*SESF
      FSS=0.5*DENSE*(U**2)*ASCS
      FDSS=0.5*DENSE*(U**2)*CSDS
      CLCF=5.15*ALFAC+0.036*FLAP+0.13
      FLC=0.5*DENSE*(U**2)*ACF*CLCF
      FDC=0.5*DENSE*(U**2)*ACF*COEFCX
      CLPF=4.10*ALFAP
      FLP=0.5*DENSE*(U**2)*APF*CLPF
      FDP=0.5*DENSE*(U**2)*APF*COEFPX
      CLSF=4.10*ALFAS
      FLS=0.5*DENSE*(U**2)*ASF*CLSF
      FDS=0.5*DENSE*(U**2)*ASF*COEFSX
```

```
      CLMF=5.15*ALFAM
      FLM=0.5*DENSE*(U**2)*AMF*CLMF
      FDM=0.5*DENSE*(U**2)*AMF*COEFMX
      FLCZ=0.5*DENSE*(U**2)*ACF*CLCF
      FDCZ=0.5*DENSE*(U**2)*ACF*COEFCX
      FLPZ=0.5*DENSE*(U**2)*APF*CLPF
      FDPZ=0.5*DENSE*(U**2)*APF*COEFPX
      FLSZ=0.5*DENSE*(U**2)*ASF*CLSF
      FDSZ=0.5*DENSE*(U**2)*ASF*COEFSX
      FLMZ=0.5*DENSE*(U**2)*AMF*CLMF
      FDMZ=0.5*DENSE*(U**2)*AMF*COEFMX
*
*     TRANSFORMATION TO BODY AXES
*
      FXCF=-FDC+ALFAC*FLC
      FXPF=-FDP+ALFAP*FLP
      FXSF=-FDS+ALFAS*FLS
      FXMF=-FDM+ALFAM*FLM
      FXCS=-FDSC-BETAC*FSC
      FXPS=-FDPS-BETAP*FPS
      FXSS=-FDSS-BETAS*FSS
      FYCS=-BETAC*FDSC+FSC
      FYPS=-BETAP*FDPS+FPS
      FYSS=-BETAS*FDSS+FSS
      FZCF=-FDCZ*ALFAC-FLCZ
      FZPF=-FDPZ*ALFAP-FLPZ
      FZSF=-FDSZ*ALFAS-FLSZ
      FZMF=-FDMZ*ALFAM-FLMZ
      LZCS=LZCF-0.4*SECF
      LZPS=LZPF-0.4*SEPF
      LZSS=LZSF-0.4*SESF

   -  THRUST TRIM ROUTINE

* * * * * * * * * * * * * * * * * * * *
*                                      *
      FXONE=FXCF+FXPF+FXSF+FXMF+FXCS+FXPS+FXSS
*     FX1=FXONE+FGRAX+TX                 *
      TX1=TX-FX1
*     IF(TX1.LT.0.0) TX1=TX/2.0          *
      TEST=TX-TX1
*     IF(IFLAG1.EQ.0) TX=TX1             *
      IF(ABS(TEST).LT.EPS) IFLAG1=1
*                                      *
* * * * * * * * * * * * * * * * * * * *
```

```
*
*       SUMMATION OF FORCES AND MOMENTS
*
        FX=FXONE+FGRAX+TX
        UDOT=(1./MASS)*FX-Q*W
        IF(IFLAG1.EQ.0) UDOT=0.0
        FY=FYCS+FYPS+FYSS+FGRAY
        FZ=FZCF+FZPF+FZSF+FZMF+FGRAZ
        L=FZPF*LYPF+FZSF*LYSF-FYPS*LZPS-FYSS*LZSS-FYCS*LZCS
        MFWD=FZCF*LXCF
        M = - MFWD  -FZPF*LXPF-FZSF*LXSF-FZMF*LXMF+FXCF*LZCF+FXPF*LZPF...
        +FXSF*LZSF+FXMF*LZMF+FXCS*LZCS+FXPS LZPS+FXSS*LZSS+TX*LZT
        N=FYCS*LXCS+FYPS*LXPS+FYSS*LXSS
*
*       VELOCITY INTEGRALS
*
SORT
*
        VDOT=(1./MASS)*FY-R*U
        WDOT=(1./MASS)*FZ+Q*U
        PDOT=(1.0/IXX)*L
        QDOT=(1.0/IYY)*M
        RDOT=(1.0/IZZ)*N
        U=INTGRL(UINIT,UDOT)
        V=INTGRL(0.0,VDOT)
        W=INTGRL(0.0,WDOT)
        P=INTGRL(0.0,PDOT)
        Q=INTGRL(0.0,QDOT)
        R=INTGRL(0.0,RDOT)

        AUTOMATIC CONTROL BLOCK

* * * * * * * * * * * * * * * * * * * *
*                                      *
        HACT=-ZE+LXH*THETA
*       DELH=HREF-HACT                 *
        AZC=FZ/MASS-LXCF*QDOT
*       FLAP1=(GAIN1*DELH+GAIN3*AZC-GAIN4*THETA)*GAINC   *
        FLAP=LEDLAG(0.0,0.10,0.16,FLAP1)
*                                      *
* * * * * * * * * * * * * * * * * * * *
```

```
*
DYNAMIC
*

      DISTURBANCE BLOCK

      TEST1=IMPULS(2.0,30.0)
      TEST2=PULSE(TEST1,0.2)
      TEST3=0.07*TEST2
      GO TO (1,2),NCUR
    1 Q=Q+TEST3
    2 CONTINUE
*
SAMPLE
*
      NUM=NUM+1
      CALL DRWG(1,NCUP,NUM,TIME,ZE)
      CALL DPWG(2,NCUR,NUM,TIME,THETA)
      CALL DRWG(3,NCUR,NUM,TIME,Q)
*
TERMINAL
*
      IF(NCUR.EQ.2) GO TO 10
      NCUR=NCUR+1
      CALL RERUN
      RETURN
   10 CALL ENDRW(NPLOT)
END
STOP
//L.SYSLIB  DD  DISP=SHR,DSN=SYS1.DSL,
//      VOL=SER=MARY,UNIT=2314
//      DD  DISP=SHR,DSN=SYS1.FORTLIB
//      DD  DISP=SHR,DSN=SYS1.MPSLIB
//      DD  DISP=SHR,DSN=S1269.HYDROFL,
//      VOL=SER=CEL001,UNIT=2321
//G.FT03F001 DD DSN=S1269.GLOP,UNIT=2321,DISP=SHR,
//      VOL=SER=CEL001,LABEL=(,,,IN)
//PLOT.SYSIN DD *
```

ANGLE OF ATTACK ROUTINE

THIS PROGRAM WAS WRITTEN TO OBTAIN THE VALUES OF THE
ANGLE OF ATTACK AND THRUST NECESSARY TO BALANCE
THE EQUATIONS OF MOTION. ONCE THE VALUES WERE
OBTAINED, THE PROGRAM WAS NO LONGER USED.

```
// EXEC FORTCLG
//FORT.SYSIN DD *
      COMMON MATRIX(539)
      REAL IXX,IYY,IZZ,LAMDA,LXCF,LXCS,LXPF,LXPS,LXSF,LXSS,LXMF,LZCF,
     1LZCS,LZPF,LZPS,LZSF,LZSS,LZMF,LXT,LZT,LXH,M
      DATA          WEIGHT/262527.0/,IXX/601200.0/,IYY/42860000.0/,IZZ/
     141740000.0/,       PI/3.141593/,LAMDA/100.0/,THETA1/0.0/,
     1PHI1/0.0/,IFLAG/0/,U/60.0/,ACF/65.4/,APF/36.8/,ASF/36.8/,AMF/76.0/
     2,LXCF/41.59/,LXCS/41.59/,LXPF/-16.98/,LXPS/-16.98/,LXSF/-16.98/,LX
     3SS/-16.98/,LXMF/-16.98/,LZCF/15.5/,LZCS/13.25/,LZPF/17.14/,LZPS/14
     4.0/,LZSF/17.14/,LZSS/14.0/,LZMF/17.14/,LXT/-16.9/,LZT/17.7/,LXH/68
     5.0/,ZE/-11.5/,PSI1/0.0/,G/32.2/
      TX=19291.8
      DENSF=2.0
      P=0.0
      Q=0.0
      R=0.0
      V=0.0
      W=0.0
      MASS=WEIGHT/G
      CONV=PI/180.0
      FLAP=0.0
      FLAG=0.0
      IF(IFLAG.EQ.0) CALL SETUP(FLAG)
      IF(FLAG.EQ.1) STOP
      TOLFX=2000.0
      TOLFM=1000.0
      A=0.001
      B=0.002
      ALF=0.03
      ALP=0.075
      ALS=0.075
      ALM=0.075
      PHI=CONV*PHI1
      THETA=CONV*THETA1
      PSI=CONV*PSI1
```

```
C
C     SUBMERGENCE TERMS
C
      SECF=ZE-LXCF*THETA+LZCF*COS(PHI)
      SEPF=ZE-LXPF*THETA+LYPF*SIN(PHI)+LZPF*COS(PHI)
      SESF=ZE-LXSF*THETA+LYSF*SIN(PHI)+LZSF*COS(PHI)
      SEMF=ZE-LXMF*THETA+LZMF*COS(PHI)
      ALIMH=10.0*CONV
      ALIML=-6.0*CONV
   14 IFLAG=0
C
C     ANGLES OF ATTACK AND SIDE SLIP
C
    4 VRC=V-LZCF*P+LXCF*R
      VRS=V-LZSF*P+LXSF*R
      VRM=V
      VRP=V-LZPF*P+LXPF*R
      WRP=W+LYPF*P-LXPF*Q
      WRS=W+LYSF*P-LXSF*Q
      WRM=W-LXMF*Q
      WRC=W-LXCF*Q
      ALFAC=WRC/U+ALF
      ALFAP=WRP/U+ALP
      ALFAS=WRS/U+ALS
      ALFAM=WRM/U+ALM
      BETAC=VRC/U
      BETAP=VRP/U
      BETAS=VRS/U
C
C     HYDRODYNAMIC COEFFICIENTS
C
      CALL INTERP(ALFAC,FLAP,COEFCX,2)
      CALL INTERP(ALFAP,FLAP,COEFPX,3)
      CALL INTERP(ALFAS,FLAP,COEFSX,3)
      CALL INTERP(ALFAM,FLAP,COEFMX,1)
      CALL INTRP1(BETAC,SECF,CFDS,2,THETA,THETA1)
      CALL INTRP1(BETAP,SEPF,CPDS,1,THETA,THETA1)
      CALL INTRP1(BETAS,SESF,CSDS,1,THETA,THETA1)
      FGRAX=-MASS*G*SIN(THETA)
      FGRAZ=MASS*G*COS(PHI)
C
C     FORCES IN WATER AXES
C
      CCS=-2.15*BETAC
      ACCS=CCS*4.25*SECF
      FSC=0.5*DENSE*(U**2)*ACCS
      FDSC=0.5*DENSE*(U**2)*CFDS
      PCS=-2.15*BETAP
```

```
      APCS=PCS*4.25*SEPF
      FPS=0.5*DENSE*(U**2)*APCS
      FDPS=0.5*DENSE*(U**2)*CPDS
      SCS=-2.15*BETAS
      ASCS=SCS*4.25*SESF
      FSS=0.5*DENSE*(U**2)*ASCS
      FDSS=0.5*DENSE*(U**2)*CSDS
      CLCF=5.15*ALFAC+0.13
      FLC=0.5*DENSE*(U**2)*ACF*CLCF
      FDC=0.5*DENSE*(U**2)*ACF*COEFCX
      CLPF=4.10*ALFAP
      FLP=0.5*DENSE*(U**2)*APF*CLPF
      FDP=0.5*DENSE*(U**2)*APF*COEFPX
      CLSF=4.10*ALFAS
      FLS=0.5*DENSE*(U**2)*ASF*CLSF
      FDS=0.5*DENSE*(U**2)*ASF*COEFSX
      CLMF=5.15*ALFAM
      FLM=0.5*DENSE*(U**2)*AMF*CLMF
      FDM=0.5*DENSE*(U**2)*AMF*COEFMX
      FLCZ=0.5*DENSE*(U**2)*ACF*CLCF
      FDCZ=0.5*DENSE*(U**2)*ACF*COEFCX
      FLPZ=0.5*DENSE*(U**2)*APF*CLPF
      FDPZ=0.5*DENSE*(U**2)*APF*COEFPX
      FLSZ=0.5*DENSE*(U**2)*ASF*CLSF
      FDSZ=0.5*DENSE*(U**2)*ASF*COEFSX
      FLMZ=0.5*DENSE*(U**2)*AMF*CLMF
      FDMZ=0.5*DENSE*(U**2)*AMF*COEFMX
C
C     TRANSFORMATIONS TO BODY AXES
C
      FXCF=-FDC+ALFAC*FLC
      FXPF=-FDP+ALFAP*FLP
      FXSF=-FDS+ALFAS*FLS
      FXMF=-FDM+ALFAM*FLM
      FXCS=-FDSC-BETAC*FSC
      FXPS=-FDPS-BETAP*FPS
      FXSS=-FDSS-BETAS*FSS
      FZCF=-FDCZ*ALFAC-FLCZ
      FZPF=-FDPZ*ALFAP-FLPZ
      FZSF=-FDSZ*ALFAS-FLSZ
      FZMF=-FDMZ*ALFAM-FLMZ
      LZCS=LZCF-0.4*SECF
      LZPS=LZPF-0.4*SEPF
      LZSS=LZSF-0.4*SESF
```

```
C
C     SUMMATION OF FORCES IN X AND Z DIRECTIONS
C
      FXONE=FXCF+FXPF+FXSF+FXMF+FXCS+FXPS+FXSS
      FX=FXONE+FGRAX+TX
      FZ=FZCF+FZPF+FZSF+FZMF+FGRAZ
      WRITE(6,102)FZ,ALF,ALM
      IF(FZ.GT.TOLEX) GO TO 2
      IF(FZ.LT.-TOLEX) GO TO 1
      GO TO 8
    1 ALF=ALF-A
      ALM=ALM-A
      ALP=ALP-A
      ALS=ALS-A
      GO TO 10
    2 ALF=ALF+B
      ALM=ALM+B
      ALP=ALP+B
      ALS=ALS+B
      GO TO 10
C
C     SUMMATION OF THE MOMENT ABOUT THE Y-AXES
C
    3 M=-FZCF*LXCF-FZPF*LXPF-FZSF*LXSF-FZMF*LXMF+FXCF*LZCF+FXPF*LZPF+FXS
     1F*LZSF+FXMF*LZMF+FXCS*LZCS+FXPS*LZPS+FXSS*LZSS+TX*LZT
      WRITE(6,100) M,ALF,ALM
      IF(M.GT.TOLEM)GO TO 5
      IF(M.LT.-TOLEM)GO TO 6
      GO TO 7
    5 ALF=ALF-A/5.0
      ALM=ALM+A/5.0
      ALP=ALP+A/5.0
      ALS=ALS+A/5.0
      IFLAG=1
      GO TO 10
    6 ALF=ALF+A/3.0
      ALM=ALM-A/3.0
      ALP=ALP-A/3.0
      ALS=ALS-A/3.0
      IFLAG=1
      GO TO 10
    7 IF(IFLAG.EQ.1)GO TO 14
      WRITE(6,101)ALF,ALM
  101 FORMAT('0','FINAL,A-S:  ALF=',F10.6,1X,'ALM=',F10.6)
  100 FORMAT(' ','M=',E14.8,1X,'ALF=',F10.6,1X,'ALM=',F10.6)
  102 FORMAT(' ','FZ=',E14.8,1X,'ALF=',F10.6,1X,'ALM=',F10.6)
      STOP
    8 IF(ABS(FX).GT.TOLEX) GO TO 9
```

```
      GO TO 3
    9 TX1=TX-FX
      IF(TX1.LT.0.0) TX1=TX/2.0
      WRITE(6,103) TX,FX,TX1
  103 FORMAT('0','TX=',E14.8,1X,'FX=',E14.8,1X,'TX1=',E14.8)
      TX=TX1
      GO TO 3
   10 IF(ALF.GT.ALIMH) ALF=ALIMH
      IF(ALF.LT.ALIML) ALF=ALIML
      IF(ALM.GT.ALIMH) GO TO 11
      IF(ALM.LT.ALIML) GO TO 12
      GO TO 4
   11 ALM=ALIMH
      ALS=ALIMH
      ALP=ALIMH
      GO TO 4
   12 ALM=ALIML
      ALP=ALIML
      ALS=ALIML
      GO TO 4
      END
```

SUBROUTINE SETUP

```
      THIS SUBROUTINE FORMS THE DATA POINTS COMPRISING
      THE CURVES OF FOIL AND STRUT DRAG COEFFICIENTS
      AND SIDE SLIP COEFFICIENTS INTO MATRACES.

      SUBROUTINE SETUP(FLAG)
      COMMON COEFMX,COEFCX,COEFOX,CFDS1,CADS1
      DIMENSION COEFCX(3,33),COEFOX(3,33),COEFMX(3,33),CFDS1(11,11),CADS
     11(11,11),INFO(8)
      REAL INFO
      IC=0
      IFLAG=0
      IFLAG1=0
      MATRIX=1
      J=0
      K=1
      ICOUNT=0
    2 READ(3,100,END=50) INFO
  100 FORMAT(8F10.5)
      I1=1
      IF(IFLAG1.EQ.1) GO TO 51
      GO TO (4,5,6,7,8),MATRIX
    4 CONTINUE
      DO 1 I=1,8
      J=J+1
      IF(J.GT.3) K=K+1
      IF(J.GT.3) J=1
      COEFOX(J,K)=INFO(I)
      ICOUNT=ICOUNT+1
      IC=IC+1
      IF(ICOUNT.EQ.99) GO TO 3
    1 CONTINUE
      GO TO 2
    3 I1=I
      IF(I1.LE.8) I1=I1+1
      J=0
      K=1
      ICOUNT=0
      MATRIX=2
    5 IF(I1.GT.8) GO TO 2
      DO 9 I=I1,8
      J=J+1
      IF(J.GT.3) K=K+1
      IF(J.GT.3) J=1
```

```
      COEFCX(J,K)=INFO(I)
      ICOUNT=ICOUNT+1
      IC=IC+1
      IF(ICOUNT.EQ.99) GO TO 10
    9 CONTINUE
      GO TO 2
   10 I1=I
      IF(I1.LE.8) I1=I1+1
      J=0
      K=1
      ICOUNT=0
      MATRIX=3
    6 IF(I1.GT.8) GO TO 2
      DO 11 I=I1,8
      J=J+1
      IF(J.GT.3) K=K+1
      IF(J.GT.3) J=1
      COEFMX(J,K)=INFO(I)
      ICOUNT=ICOUNT+1
      IC=IC+1
      IF(ICOUNT.EQ.99) GO TO 12
   11 CONTINUE
      GO TO 2
   12 I1=I
      IF(I1.LE.8) I1=I1+1
      J=0
      K=1
      ICOUNT=0
      MATRIX=4
    7 IF(I1.GT.8) GO TO 2
      DO 13 I=I1,8
      J=J+1
      IF(J.GT.11) K=K+1
      IF(J.GT.11) J=1
      CADS1(J,K)=INFO(I)
      ICOUNT=ICOUNT+1
      IC=IC+1
      IF(ICOUNT.EQ.121) GO TO 15
   13 CONTINUE
      GO TO 2
   15 I1=I
      IF(I1.LE.8) I1=I1+1
      J=0
      K=1
      ICOUNT=0
      MATRIX=5
    8 IF(I1.GT.8) GO TO 2
      DO 14 I=I1,8
```

```
      J=J+1
      IF(J.GT.11) K=K+1
      IF(J.GT.11) J=1
      CFDS1(J,K)=INFO(I)
      ICOUNT=ICOUNT+1
      IC=IC+1
      IF(ICOUNT.EQ.121) GO TO 16
   14 CONTINUE
      GO TO 2
   16 IFLAG1=1
      GO TO 2
   50 IFLAG=1
      IF((IFLAG.EQ.1).AND.(IFLAG1.EQ.1)) GO TO 52
   51 WRITE(6,104) ICOUNT,MATRIX,IC
  104 FORMAT(' ','JOB FAILURE',1X,'COUNT=',I6,1X,'MATRIX=',I6,1X,'NO. PT
     1S=',I6)
      FLAG=1.0
      RETURN
   52 WRITE(6,105) IC
  105 FORMAT(' ','JOB COMPLETE',1X,'POINTS STORED=',I6)
      RETURN
      END
```

SUBROUTINE INTERP

```
      SUBROUTINE INTERP(ALFAC,FLAP,COEF,M)
      COMMON COEFMX,COEFCX,COEFOX
      DIMENSION COEFMX(3,33),COEFCX(3,33),COEFOX(3,33)                  CHA00020
      DATA CONDEG/57.295773/
      ALFA=ALFAC*CONDEG
      IF(ALFA.GT.10.0) WRITE(6,100)ALFAC,M                              CHA00040
      IF(ALFA.GT.10.0) ALFA=10.0                                        CHA00050
  100 FORMAT('0','ERROR.ALFA EXCEEDED LIMITS.ALFA=',E14.8,2X,'M=',I1)
      IF(ALFA.LT.-6.0) WRITE(6,100) ALFAC,M                             CHA00070
      IF(ALFA.LT.-6.0) ALFA=-6.0                                        CHA00080
      ALPHA=2.0*ALFA                                                    CHA00090
      IF(ALPHA.LT.0.0) GO TO 1                                          CHA00100
      IF(ALPHA.GT.0.0) GO TO 2                                          CHA00110
      IA=13                                                             CHA00120
      WTA=0.0                                                           CHA00130
      GO TO 3                                                           CHA00140
    1 IA1=-ALPHA                                                        CHA00150
      IA=13-IA1                                                         CHA00160
      ALPHA1=-IA1                                                       CHA00170
      WTA=ALPHA-ALPHA1                                                  CHA00180
      GO TO 3                                                           CHA00190
    2 IA1=ALPHA                                                         CHA00200
      IA=13+IA1                                                         CHA00210
      ALPHA1=IA1                                                        CHA00220
      WTA=ALPHA-ALPHA1                                                  CHA00230
    3 IF(FLAP.LT.-5.0) WRITE(6,101) FLAP                                CHA00240
      IF(FLAP.LT.-5.0) FLAP=-5.0                                        CHA00250
      IF(FLAP.GT.5.0) WRITE(6,101) FLAP                                 CHA00260
      IF(FLAP.GT.5.0) FLAP=5.0                                          CHA00270
  101 FORMAT('0','ERROR.FLAP EXCEEDED LIMITS.FLAP=',E14.8)
      IF(FLAP)4,5,6                                                     CHA00290
    4 IB=1                                                              CHA00300
      WTB=-((5.0+FLAP)/5.0)                                             CHA00310
      GO TO 7                                                           CHA00320
    5 IB=2                                                              CHA00330
      WTB=0.0                                                           CHA00340
      GO TO 7                                                           CHA00350
    6 IB=3                                                              CHA00360
      WTB=(5.0-FLAP)/5.0                                                CHA00370
    7 IF(WTA)8,9,10                                                     CHA00380
    8 IA2=IA-1                                                          CHA00390
      GO TO 11                                                          CHA00400
    9 IA2=IA                                                            CHA00410
      GO TO 11                                                          CHA00420
```

```
10   IA2=IA+1                                          CHA00430
11   IF(WTB)12,13,12                                   CHA00440
12   IB2=2                                             CHA00450
     GO TO 14                                          CHA00460
13   IB2=IB                                            CHA00470
14   GO TO(15,16,17),M                                 CHA00480
15   COEF1=COEFMX(IB,IA)                               CHA00490
     COEF2=COEFMX(IB2,IA)                              CHA00500
     GO TO 18                                          CHA00510
16   COEF1=COEFCX(IB,IA)                               CHA00520
     COEF2=COEFCX(IB2,IA)                              CHA00530
     GO TO 18                                          CHA00540
17   COEF1=COEFOX(IB,IA)                               CHA00550
     COEF2=COEFOX(IB2,IA)                              CHA00560
18   COEF3=(COEF2-COEF1)*ABS(WTB)+COEF1                CHA00570
     GO TO (19,20,21),M                                CHA00580
19   COEF1P=COEFMX(IB,IA2)                             CHA00590
     COEF2P=COEFMX(IB2,IA2)                            CHA00600
     GO TO 22                                          CHA00610
20   COEF1P=COEFCX(IB,IA2)                             CHA00620
     COEF2P=COEFCX(IB2,IA2)                            CHA00630
     GO TO 22                                          CHA00640
21   COEF1P=COEFOX(IB,IA2)                             CHA00650
     COEF2P=COEFOX(IB2,IA2)                            CHA00660
22   COEF3P=(COEF2P-COEF1P)*ABS(WTB)+COEF1P            CHA00670
     COEF=(COEF3P-COEF3)*ABS(WTA)+COEF3                CHA00680
     RETURN
     END                                               CHA00690
```

SUBROUTINE INTRP1

```
      SUBROUTINE INTRP1(BETA1,SOB,COEFS,M,THETA,THETA1)
      COMMON JUNK,CFDS1,CADS1
      DIMENSION JUNK(297),CFDS1(11,11),CADS1(11,11)
      DATA CONDEG/57.295773/
      SUB=SOB
      BETA=BETA1*CONDEG
      IF(BETA.GT.5.0) WRITE(6,100) BETA1,M
      IF(BETA.GT.5.0) BETA=5.0
  100 FORMAT('0','ERROR.BETA EXCEEDS LIMITS.BETA=',E14.8,2X,'M=',I1)
      IF(BETA.LT.-5.0) WRITE(6,100) BETA1,M
      IF(BETA.LT.-5.0) BETA=-5.0
      IF(BETA.LT.0.0) GO TO 1
      IF(BETA.GT.0.0) GO TO 2
      IA=6
      WTA=0.0
      GO TO 3
    1 IA1=-BETA
      IA=6-IA1
      BETAG=-IA1
      WTA=BETA-BETAG
      GO TO 3
    2 IA1=BETA
      IA=6+IA1
      BETAG=IA1
      WTA=BETA-BETAG
    3 IF(SUB.LT.0.0) SUB=0.0
      IF(SUB.GT.10.0) SUB=10.0
      IF(SUB.GT.0.0) GO TO 5
      IS=1
      WTS=0.0
      GO TO 7
    5 IS1=SUB
      IS=IS1+1
      SUB1=IS1
      WTS=SUB-SUB1
    7 IF(WTA)8,9,10
    8 IA2=IA-1
      GO TO 11
    9 IA2=IA
      GO TO 11
   10 IA2=IA+1
   11 IF(WTS.GT.0.0) GO TO 12
      IS2=IS
      GO TO 15
```

```
12 IS2=IS+1
15 IF(M.EQ.2) GO TO 16
   COEF1=CADS1(IS,IA)
   COEF2=CADS1(IS2,IA)
   GO TO 18
16 COEF1=CFDS1(IS,IA)
   COEF2=CFDS1(IS2,IA)
18 COEF3=(COEF2-COEF1)*WTS+COEF1
   IF(M.EQ.2) GO TO 20
19 COEF1P=CADS1(IS,IA2)
   COEF2P=CADS1(IS2,IA2)
   GO TO 22
20 COEF1P=CFDS1(IS,IA2)
   COEF2P=CFDS1(IS2,IA2)
22 COEF3P=(COEF2P-COEF1P)*WTS+COEF1P
   COEFS=(COEF3P-COEF3)*ABS(WTA)+COEF3
   THETA1=THETA*CONDEG
   RETURN
   END
```

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